JOURNAL OF THE AMERICAN WELDING SOCIETY

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SYMPOSIUMS MADE USEFUL

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Symposium sessions at Society meetings seldom justify the trouble it takes to arrange them. This is to be regretted, for the basic plan of a symposium—the focusing of individual and diverse opinions on a single, vital, live question—is essential to all progress. The fault lies not in the idea itself but in its execution. To take a current example: A typical symposium formed a part of the AMERICAN WELDING SOCIETY program last week, and ten or a dozen papers on weld ductility were read. All were good papers, but at the end of the session the audience had been bombarded with so many opinions and data that the average listener did not know who was for and who was against ductility, much less what the significance of the meeting might be to himself. Obviously a summation and a review of the data presented were badly needed. Fortunately for the audience and incidentally for the program makers, J. H. Critchett, Vice-President, Union Carbide & Carbon Research Laboratories, voluntarily chose to supply the needed review and a critical analysis. A session that had dropped to the level of dull recitation was converted, thus, simply into the most stimulating, thought-provoking one of the entire meeting. A lawyer would never consider permitting a jury to retire without summing up for it the many points of evidence that had been presented. Why should program committees do less for their audiences? Every symposium that is worth organizing is worth summarizing by an able review.

Change in Building Code

Upon the recommendation of the Committee on Building Codes the following change in connection with PAINTING has been approved by the Executive Committee of the Society.

> Structural steel shall not be painted on any areas where shop or field welding is later to be performed, except that a coat of linseed oil without pigment may be used for temporary protection.

COMMITTEE APPOINTMENTS

The following committee appointments have been made by the President and approved by the Board of Directors:

Executive

F. P. McKibben, Chairman
J. J. Crowe
J. H. Deppeler
R. S. Donald
E. A. Doyle
E. H. Ewertz
F. M. Farmer
G. D. Fish
A. E. Gaynor
O. E. Hovey
D. S. Jacobus
C. A. McCune
A. G. Oehler
H. S. Smith
G. D. Spackman
P. W. Swain
J. B. Tinnon
E. Vom Steeg

Finance

C. A. McCune, Chairman
J. J. Crowe
E. H. Ewertz
F. M. Farmer
A. G. Oehler
E. Vom Steeg

Meetings and Papers Committee

J. B. Tinnon, Chairman
W. Spraragen, Secretary
R. S. Donald
T. C. Fetherston
F. T. Llewellyn
A. G. Oehler
F. E. Rogers
P. W. Swain
E. Vom Steeg, Jr.

Membership

A. E. Gaynor, Chairman
W. Spraragen, Secretary
F. J. Giroux
J. W. Gray
H. J. Grow
C. Kandel
J. B. Tinnon

Revision of By-Laws

A. M. Candy, Chairman
And Section Representatives

OFFICERS OF AMERICAN BUREAU OF WELDING

The Officers of the American Bureau of Welding were re-elected to serve for another year. They are:

Director—C. A. Adams
First Vice-Director—H. M. Hobart
Second Vice-Director—J. H. Critchett
Secretary—W. Spraragen

The following were appointed to serve as an Executive Committee:

Chairman—C. A. Adams
Secretary—W. Spraragen
J. H. Critchett
J. J. Crowe
J. H. Deppeler
F. M. Farmer
H. M. Hobart
C. A. McCune
F. P. McKibben
L. S. Moisseiff
E. M. T. Ryder
H. L. Whittemore

NEW COMMITTEES

The following committees were appointed at the Board of Directors' meeting:

Legislative Committee.—As authorized at the March 1st Executive Committee meeting, President Doyle announced his appointment of the following men to serve on the Legislative Committee: Messrs. H. S. Smith, Chairman, J. H. Deppeler, D. S. Jacobus, L. D. Meeker and W. Spraragen.

Federal Board for Vocational Education.—Contact Committee to assist in the preparation of outlines of courses in specific fields of welding. In accordance with authority vested in him at the April 5th Executive Committee meeting, President Doyle announced that he had invited Professor McKibben to serve as Chairman of the Contact Committee and had proposed to Professor McKibben the name of Herman Ullmer, Linde Air Products Company, as contact man in the aircraft welding industry. It is his opinion that the selection of contact men for the other industries could be given consideration as occasion arises.

Convention Committee.—The President appointed a Convention Committee consisting of the following personnel.

Chairman of the Manufacturers' Committee, Chairman of the Meetings and Papers Committee, Chairman and Secretary of the Local Section where meeting is to be held, National Treasurer and Secretary, with Mr. C. A. McCune as Chairman of the Convention Committee for the year 1932.

In Memoriam

Harry N. Van Deusen, Materials Engineer, Bell Telephone Laboratories, New York, and a member of the American Welding Society, died suddenly on May 15th at the Easton Hospital, Easton, Pennsylvania. Mr. Van Deusen, who was a resident of East Orange, New Jersey, was taken ill at his summer home near Blairstown, New Jersey, and was rushed to the hospital where he died several hours later. He was forty-seven years old.

He was born in Columbia, New Jersey, a son of the late Reverend and Mrs. Albert Van Deusen. He belonged to an old Dutch family. His father was a Methodist minister.

In 1907 Mr. Van Deusen was graduated from Purdue University. He entered the employ of the Chicago Telephone Company and later became a member of the Engineering Department of the Western Electric Company, predecessor of the present Bell Telephone Laboratories. He was affiliated with the Bell System for the past twenty-three years. He had charge of engineering investigations of materials used in the telephone plant and was an authority in the field of insulating materials.

Mr. Van Deusen was also a member of the American Society for Testing Materials, American Institute of Electrical Engineers, American Society for Steel Treating and New York Electrical Society.

THE FIRST SOUTHWIDE CONFERENCE ON WELDING

Held at the Alabama Polytechnic Institute, Auburn, Alabama, on May 23–28, 1932

The Alabama Polytechnic Institute held its First Southwide Conference on Welding at Auburn, Alabama, on May 23–28, 1932. This conference was held under the direction of the Department of Industrial Engineering and Shops, with the Manufacturers and Users of Welding Equipment cooperating.

The sessions started with registration on Monday afternoon and lectures and addresses by President Bradford Knapp and Dean J. J. Wilmore. Some thirty technical papers were included.

Special Demonstrations

There were special demonstrations on:

Cutting Cast Iron and Steel
Aluminum Welding
Atomic Hydrogen Welding
Cast Iron Welding
Steel Brazing
Resistance Welding
Cutting with Propane Gas
Pipe Welding
Oxygen Lance
Stelliting
Thermit Welding
Using Electric Arc
Spraying Metal

COOPERATION WITH SECTIONS AND MEMBERS

In addressing the Board meeting, President McKibben stated that he believed the most important problem confronting the Society at the present time is the bringing about of closer relationship between the parent organization and its sections and members in distant parts. It was his opinion that more frequent personal contact is needed.

EMPLOYMENT SERVICE BULLETIN

SERVICES AVAILABLE

A-142. Welding engineer desires position as engineer, foreman or instructor. Have had twenty years' experience in oxyacetylene, arc, hand and automatic and atomic hydrogen processes. Experienced in training operators. Have developed welding departments and assisted in development and research work.

A-170. Electric welder desires position. Experienced in general repair, ship repairing and tank and pipe work.

A-171. Acetylene and electric welder desires position.

A-172. Electric welder and gas burner desires position.

A-173. Electric welder and acetylene burner desires position.

SECTION ACTIVITIES

CHICAGO

At its May meeting, the Chicago section of the AMERICAN WELDING SOCIETY had as speaker, G. N. Sieger of P. R. Mallory, Inc., Indianapolis, Ind., whose subject was "Welding and Cutting with Elkonite and Carboloy." This was an exceptionally interesting and complete discussion of the many applications of resistance welding in industry today. Mr. Sieger presented some pertinent data on present-day fabrication methods, particularly in the automotive field. He closed his discussion with details of the proper use and preparation of metal cutting tools.

Since the April meeting, several of the welded specimens, which were X-rayed and discussed at that time, were prepared for tensile test and pulled to determine their breaking point. Claude S. Gordon and Wm. G. Praed of the Claude S. Gordon X-ray Laboratories who furnished the X-ray films for the April meeting were on hand to discuss the data obtained by these different methods of testing and to show the relation of one to the other.

This was the last meeting of the Chicago section until October and at this time the newly elected officers were installed, as follows: Chairman, C. C. Whittier, Robert W. Hunt Co.; Vice-Chairman, J. B. Green, Fusion Welding Corp.; Secretary-Treasurer, M. S. Hendricks, *The Welding Engineer;* Directors for three years, J. W. Haygood, Linde Air Products Co.; A. F. Krumholz, Chicago Boiler Works, Otto Voss, Allis Chalmers Co., and I. B. Yates, Bryant Machinery & Engineering Co.

NEW YORK

One of the most successful meetings of the New York Section was held on May 24th. Nearly four hundred members and guests were in attendance. A series of papers on stainless steel, physical properties and utilization in industry were featured. The speakers included J. H. Critchett, Vice-President, Union Carbide & Carbon Research Laboratories, Inc., on "History, Classification and Metallurgy;" C. A. Scharschu, Director of Research, Allegheny Steel Co., on "Available Types, Uses and Applications;" and D. T. Haddock, Consulting Engineering, American Sheet & Tin Plate Company. Mr. F. M. Farmer, Past-President of the Society presided. The papers presented a non-technical discussion of the fundamental properties, the manufacture and fabrication, and the current uses and applications of the commercial grades of stainless steel, with particular reference to their architectural adaptations.

A feature of the meeting was a stainless steel exhibit showing the varied applications of stainless steel and its fabrication by welding.

NORTHERN NEW YORK

The following is a list of the officers and directors for the year 1932–33, as elected by ballot prior to the annual Spring Meeting of this Section held in Pittsfield, May 13th: Chairman, O. A. Tilton, General Electric Company; 1st Vice-Chairman, R. T. Gillette, General Electric Company; 2nd Vice-Chairman, L. R. Leveen, General Electric Company; Secretary and Treasurer, S. Martin, Jr., General Electric Company.

SAN FRANCISCO

The May meeting of the San Francisco Section was held on the 20th. Mr. Robert Cochrain, Engineer, James A. Nelson Co., spoke on "Welding and Heating Installation—San Francisco War Memorial Building."

PORTLAND

The May meeting of the Portland Section was held on the 24th at the Multnomah Hotel. The technical session included a paper by Mr. Davis of the Linde Air Products Company on recent changes in welding and its applications. He also showed an interesting film entitled "Linde Welding." A report was presented in regard to the Welding Congress held in Portland on April 28th to 30th. Eighteen exhibitors showed the latest materials and equipment. The following addresses were also presented: President Geo. C. Dierking's address.

"Modern Trends in Industrial Development," Dean H. J. Rogers, O. S. C., Corvallis, Ore.

"Modern Welding," A. J. Bissell, Consulting Welding Engineer, Seattle, Washington.

"Modern Application of Arc Welding," Paper prepared by A. M. Candy, Engineer, Westinghouse Electric & Mfg. Co.

"Application of Cutting and Welding in the Lumber Industry," W. E. Wiebenson, Linde Air Products Co., Portland, Ore.

"The Old Time Blacksmith," Jimmie Cranna, Municipal Shops, Portland, Ore.

"The New Time Blacksmith," W. P. Kellogg, Air Reduction Sales Co., Portland, Oregon. Assisted by Fred L. Huggins, Chas. Beckwith, Geo. Clark and E. R. Hodson.

"Practical Welding Methods," H. B. Isings, Woodbury & Co., Portland, Ore.

"Hard Surfacing Methods," Ralph S. Beeler, J. E. Haseltine & Co., Portland, Oregon.

Flame Cutting of Low-Carbon Steel

By J. R. DAWSON

†Paper presented at October 20, 1931, Meeting of New York Section, American Welding Society, by J. R. Dawson of the Union Carbide and Carbon Res. Labs., Long Island City, N. Y.

THE flame cutting of steel is so easily carried out and its results have been so satisfactory that the operation has earned the favorable consideration of practically every-one working with this material. It has contributed to the progress of welding in steel construction and without question it will be developed into an even more efficient tool than it is at present.

Some years ago the cutting of steel by the oxy-acetylene flame was regarded with considerable suspicion, but experience in the use of parts cut by this means has been very favorable, and investigations

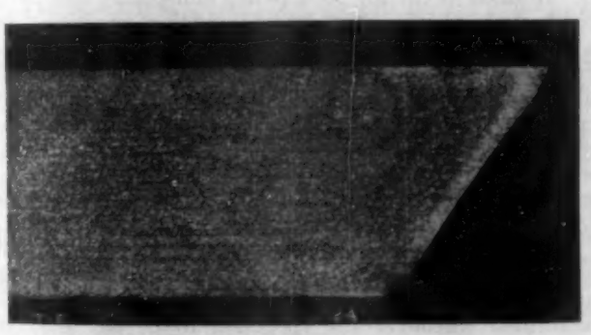

Fig. 1.—The 5/8 In. Thick Low-Carbon Steel Specimen Illustrated in Fig. 1 at 4 Diameters Was Cut Along the Right-Hand Edge. The Structure Was Affected by the Heat to the Depth Shown by the Light Colored Band Along the Edge. The Depth Was Less Than 1/16 In.

carried out by leaders in steel construction have shown that such steel is entirely suitable for use in structures, with the result that objections to flame cutting are now very seldom encountered. This paper will consist largely of a review of information developed in the course of various Laboratory investigations of flame cutting.

The steels to be cut fall into two distinct classes, low-carbon steel and higher-carbon or alloy steels. Steels of the latter division, when required for severe service, are usually preheated before cutting, while low-carbon steels, such as fire-box plate and structural shapes, do not require preheating.

The heating effect of the high temperature to which the cut edge is subjected and the carburization of the cut edge are magnified in the higher carbon steels. Low-carbon steel, in its rolled condition, is composed of ferrite and pearlite. The structure is changed when the steel is heated red hot, and the new structure is called "sorbite." It is different because it cooled more rapidly than after the original rolling. Sorbite gives the steel greater strength while causing very little reduction in ductility. It would be desirable if structural steels could be made to have a microstructure

Fig. 2—Hand-Cut 1/2 In. Thick Boiler Plate Bent through 180° Without Failure Starting at Cut Edges

consisting entirely of sorbite, but to do this would add greatly to the cost and difficulties of manufacture.

The amount of the strengthening has been illustrated by tensile tests of A. S. T. M. standard flat specimens which when milled to shape had tensile strength of 55,000 lb., and when cut to shape with the flame had tensile strength of 57,000 to 58,000 lb. per sq. in. Bending tests on specimens identical in size showed that about 8% greater load was required to bend the flame-cut specimens through 180° than was necessary for the same bending of milled specimens.

The source of the carbon taken up in a flame-cut edge has been found to be in the steel itself and not in the flame. Carburization occurs even when a fuel gas free from carbon is used. This was ascertained by experiments in cutting Armco iron and again by cutting simultaneously through an upper plate of high-carbon steel and a lower plate of Armco iron. When the Armco iron was cut alone, there was substantially no carburization, but when the flame passed through high-carbon steel into the Armco iron, carburization occurred to a marked extent. It is interesting to note that moderate preheating of the high-carbon steels prevents carburization and also that there is only slight increase of carbon at the edge of low-carbon steels which are cut without preheating.

Flame cutting is sometimes needed for preparing edges that are to be welded. Such edges can readily be made freer from oxide than the original steel plate with its mill-scale surface. Smooth cutting is desirable in this case because in the welding of a rough edge it would be necessary to melt deeply enough to insure

Fig. 3—Top Face in Illustration Cut on Oxyacetylene Machine, Then Bent in Press as Shown Without Failure Starting. Material 1 1/2 In. Thick Structural Steel

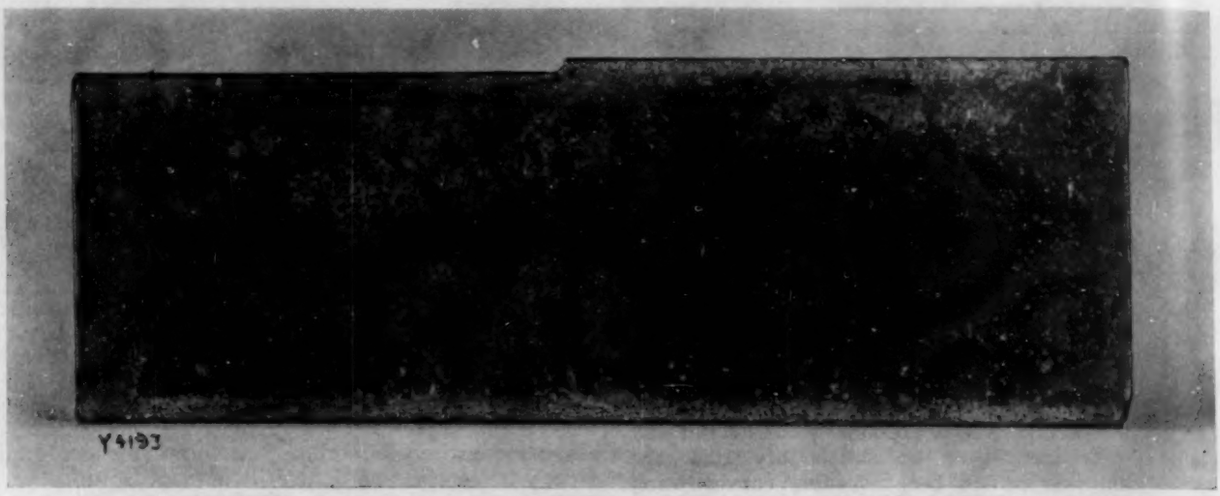

Fig. 4—Straight Smooth Edge Obtained When Only $^1/_{16}$ In. Metal Was Removed from $1^1/_4$ In. Thick Specimen

fusion entirely to the bottom of the small depressions. Smooth cutting should always be aimed at as an indication of good workmanship and also because a steel specimen with a regular surface will withstand greater deformation than one with irregular finish. This is true regardless of the method of preparation. Most workmen can learn to cut with fair smoothness by hand, if the steel is placed so that a suitable working position is possible. Various guides or supports for the torch have also been used with advantage. When the cutting is done by machine the smoothness depends upon the steadiness of its motion and also upon the correct choice of cutting nozzle and oxygen pressure.

The use of the word "burning" is no doubt partly responsible for the idea that the steel at the surface of a cut edge has been so changed as to have properties similar to slag or cinder. Microscopic examination shows that, from a mechanical standpoint, the steel at the edge is unchanged and that good steel extends entirely to the edge. All of the steel that has been melted and partially oxidized or mixed with oxide is blown out of the kerf. This slag contains about 35% of metallic iron and the remainder is magnetic iron oxide (Fe_3O_4). The width of the kerf ranges from about $^1/_{16}$ in. in thin steel to about $^1/_4$ in. when steel, say, 12 in. thick is cut.

The term "flame milling" has been suggested. Machine milling is customary for column footings but all other structural members are flame-cut with sufficient accuracy by devices now on the market. Tension or compression members of a truss may be cited as examples. Experiments to ascertain what precision could be obtained in cutting steel plates and beams have been conducted with a straight-line cutting machine. In a plate specimen $1^1/_4$ in. thick and 15 in. long, the variation in the cut surface was 0.008 in. in lengthwise direction and 0.002 in. in the crosswise direction. A cut specimen which would be exactly 3.50 in. wide was requested, and the specimen produced was 3.495 in. wide. In other experiments it was found that the edge would remain straight and smooth when as little as $^1/_{16}$ in. was removed by the flame.

These experiments seem to justify the conclusion that precision flame cutting may be expected in the near future. As a matter of fact, this accurate cutting can be performed whenever the specimen to be cut and the cutting torch are mounted on a sufficiently precise apparatus. With such equipment, a wide range of accurate cutting is possible. The variables in the operation, when considering range, are size of preheating flames, size of cutting oxygen orifice, pressure of cutting oxygen and rate of travel of the cutting blowpipe. When coordinated and "set" for a given condition or thickness the operations of cutting are reproducible.

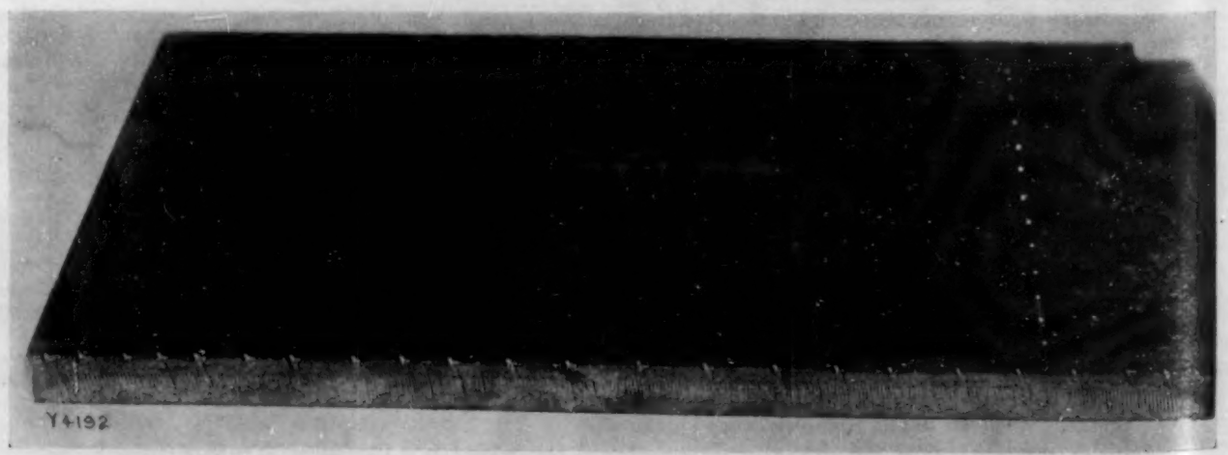

Fig. 5—Metal Removed Up to Center of Center Punch Marks Made in Straight Line. One-Half Inch Thick Steel

Machine Welding—Problems in Design and Operations

By J. L. ANDERSON

✦This paper was presented at the Annual Meeting of the American Welding Society, April 1932, by J. L. Anderson, Engineering Research Dept., Air Reduction Company, Inc.

THE modern trend of manufacturing process development is continually along lines which eliminate the need for manual control through the intensive application of human intelligence. Standardization applied to the multitude of materials entering into industry has made it possible to build machines operating singly and in groups in which neither the guiding hand nor the brain of man is required to perform their various functions, accurately, expeditiously or/and economically.

The wonderful success of such production units in all lines of industry naturally excites the desire of manufacturers employing hand methods of production to dream, plan and attempt the mechanizing of such operations, having in view the ever-entrancing goal of lower production costs in order to meet competition through the possibility of mass production applied to particular lines of manufacture.

Fusion welding practiced mainly as a manual operation, and therefore not generally recognized as a mass production process in the accepted meaning of the term, has led many to attempt the mechanizing of this operation in the production of a great variety of sheet and plate metal articles of commerce.

Unlike machine tool operations or chemical processes that utilize materials and methods which have become standardized through long experience, the application of welding by mechanical means applied to many types of products necessitates considerable trail blazing before real success can be achieved. Too often efforts are made in this direction considering only the mechanical set-up, or the mechanical motions required, disregarding the variables that must be reckoned with not only in the materials employed but those also which are developed or are encountered oftentimes as a result of or inherent in the material or in the welding process itself.

In the usual hand welding operation a grade or quality of materials may be employed, which, while not offering the ideal condition for satisfactory welding, still permit the experienced welder through the exercise of more intelligence than he is usually given credit for, to produce in a way that appears to satisfy.

The problems which may be encountered are the variation from standard of the material which he is welding, or of the addi g material, or it may be the condition of the equipment, either directly or indirectly employed in the welding operation, or it may be the previous preparatory operations inaccurately performed. Notwithstanding all this, by the exercise of intelligence, good judgment, skill and patience the welder is able to produce in an acceptable manner.

Mechanical operation of the welding torch under similar conditions would scarcely result in success unless provision is made in several portions of the apparatus to compensate for these conditions, or unless the welding method is susceptible of modification more or less independently of manual control.

In the matter of material, for instance, it may be that under fusion it foams, or perhaps it is sluggish, and does not flow freely, it may be too fluid, or it may erupt in spots as it congeals leaving cavities or unbroken bubbles. Whatever the difficulty is, it is obvious that a welding machine of itself cannot overcome these difficulties automatically, although they may be subject to correction under proper conditions through changes in procedure or adjustments in the mechanical set-up.

The same holds good to a very considerable extent if the trouble is one of variation from standard in the adding material. Much can be accomplished in the matter of securing quality material of the right kind by close cooperation with the supplier.

All of the factors directly affecting results can usually be controlled by a careful analysis of cause and effect, and the application of the proper corrective methods; but the point I want to make is, that the mere change from manual to mechanical operation cannot possibly insure the desired results, until every troublesome variable is removed or controlled.

Aside from the factors of material quality, machine and apparatus design and condition, there are numerous others which are frequently more troublesome and difficult to control, largely through lack of recognition, and these I will discuss later.

Cooperation with the material supplier has been referred to but I would like to emphasize the meaning of this word used in this connection.

Steel companies supplying large requirements to specification or otherwise, will invariably endeavor to correct or modify mill procedure, or will select and process material of known characteristics in order that specific results may be attained in welding, obviously it is more logical and more economical to apply corrective methods at the source through cooperation, even at an increased cost per ton, than it is to vary welding procedure, or technique, at probably a continuous expense, or to modify equipment, or sacrifice efficiency in the manufacturer's plant in order to secure perfection in weld metal quality. In other words, if the steel mill can, with metallurgists and other informed men, modify mill procedure, or supply material of satisfactory composition, it is foolish for the manufacturer to attempt to make similar corrections in the weld puddle with less qualified employees.

Frequently it is found that there is gas entrapped in the weld as the metal solidifies which tends to erupt in closely grouped relation leaving cavities which do not, as a rule, penetrate the entire thickness of the seam, but which are frequently referred to as pinholes, gas pockets, etc., and are invariably charged against the welding process. Experience has taught that the difficulty is generally encountered when inadequate or when improperly drawn specifications are submitted, and while material which behaves this way does not seriously affect steel quality, it does interfere with weld quality.

When gassy steel is encountered it is far more troublesome in mechanical welding operations and may not even be noticed in hand welding, due to the great difference in the welding speed. The hand welder by reason of his slower rate of progress keeps a mass of metal fluid for a longer period; obviously then, the problem is a similar one for the mechanical welding engineer, but it is not quite so simple as all that, for due to the higher welding speed and the greater concentration of heat he cannot permit the same time for fluidity to exist, due to the

possibility of overmelting, but he can, under proper conditions, prolong the melting time by progressive melting and accomplish the same or the equivalent result.

Costly errors are often made by assuming that material which has satisfactorily withstood the test of experience in some other method of production, is equally suitable for machine welding. As a matter of fact the requirements for production by machine welding methods are exacting, if high weld quality and close manufacturing tolerances are demanded. In this connection it may be well to remark that correct chemical analysis is not an assurance that weld quality will be satisfactory and the cooperation of the mill is therefore important in securing material which not only meets the chemical and physical specifications but also behaves satisfactorily when it is remelted in the welding operation.

In the matter of machine and apparatus design and maintenance, we have something that is purely mechanical and a careful analysis of results will clearly indicate to what extent the results are directly traceable to correctness of design of both machine and welding apparatus. The same is true of the results as they may be affected by machine or apparatus condition.

There are several important factors which should be considered in machine design, as they may effect the result, considering now only the facilities for holding the material to be welded, and the welding operation also as it is affected by various other factors.

Let us consider for the moment the heat effect. Heat is the basis of all welding operations and the absorption of heat brings about conditions which the welding machine or the operator must counteract in order that acceptable welds may be produced at all times.

In machine welding operations the absorption of heat, whether extremely localized or more generally distributed, sets up movement of the metal which manifests itself in various ways and the amount of movement or distortion with which the designer or operator must contend influences not only the design of the machine, but very frequently the method of heat application and dictates the necessary welding procedure, as well as mechanical and other adjustments.

The thickness of the metal to be welded and the form in which it is presented to the welding means, also govern to some extent the type of distortion which occurs. In speaking of distortion, it is not my purpose to convey the idea that the entire part is caused to warp out of shape, but rather to call attention to an extremely localized condition which occurs immediately at the welding point and which disappears almost entirely when the heat application is removed and the metal returns to normal temperature.

As an illustration we will consider first the straight butt seam weld in which there are two principal reactions with which we must contend. One is due to the rate of heat transmission which causes the metal to curl downward through surface expansion because the surface absorbs heat faster than it is transmitted throughout the thickness of the metal, and because of flexibility and greater proportion of surface to thickness, the thinner sections are most seriously affected in this respect.

The other is the distortion which is the result of restrained expansion. This is manifested by a bowing upward or downward of a portion of the edge sometimes independent of the first-mentioned result, but frequently in combination.

As a matter of fact, this distortion, usually in both forms, is always present to a greater or less degree in all welding operations, depending upon the type of material and thickness particularly when the unsupported edges are unduly exposed beyond the control portions of clamping or holding devices employed in positioning the seam edges.

It is frequently noticed that one edge of the seam will assume the raised, bowed form, while the other edge will at the same relative point take the downward curved form, or both may assume the same form, or even alternate from time to time, depending on what forces are at work in various points. This condition of distortion is more or less continuous from the beginning to the end of the seam and progresses with the welding operation. In fact, it is part and parcel of the welding operation, and compels recognition on the part of the designer of the machine, in order that the welding machine will function as effectively as it should and the welding operation be successfully performed. It is a condition of which the welding machine operator will be conscious if he is determined to produce the finest possible weld, and he will, in so far as it is possible, personally make adjustments to minimize the condition, or stipulate, if he is able, the changes in design or procedure to accomplish the desired results.

This remedy lies in one of several modifications. More concentrated heating, or more generally spread heat, depending on the means of seam control, or more positive seam control if speed is not be be sacrificed. Much can be done to minimize the results of this tendency of metal to move more or less erratically under the influence of concentrated heat by means which will restrain its erratic movement by providing means for controlled movement and oftentimes forcing this movement to assist in the performance of the welding operation, or at least utilizing and controlling the forces to improve the weld strength and often the weld quality.

Nothing has been said of the general lateral and linear expansion as this is not usually troublesome and is overshadowed to a considerable extent by the two more pronounced forms just mentioned.

Considering these remarks as applied to material which has been formed to some predetermined shape, we will find that the same forces are at work but that a totally different result is produced.

Let us first look at the welding of an open seam tube by the gas welding process.

We find that the first noticeable effect of the heat is the release of the strains introduced in the forming of the tube, and its edges tend to separate due to the heat effect on both internal and external surfaces followed by a straightening out of the curve of the upper quarter as the rolling strains are further released, which not only causes the seam edges to open further but causes them to present a perceptible angle to each other in the edge faces which were originally practically parallel.

Further heat absorption then causes the edges to assume a partially bowed form, longitudinally restrained to a considerable extent by the shape and form of the tube and more particularly by the controlling members of the welding machine, while in addition the entire tube within controlled or uncontrolled limits assumed a decidedly bowed form due to the effects previously mentioned, plus the more general but graduated heating of the entire circumference of the tube but particularly the upper quarters of the tube.

As the tube travels and the welding operation progresses, this condition of distortion reaches a maximum, and adjustments provided in the machine design for the control and utilization of such effects are made in action or otherwise, which counteract and at the same time utilize the result to produce better welds more economically than would have been possible otherwise. By this I mean, that having adjusted for this progressive distortion and to a considerable extent assumed control, it is

possible by the disposition of the heat application and its intensity to utilize the conditions set up by distortion to secure through penetration greater welding speed and more mechanical working of the metal.

Immediately the thought occurs why not deliberately set up conditions that would produce these results rather than attempt to counteract and utilize them advantageously. The answer is, that regardless of the steps taken to duplicate in the cold state conditions which occur, under heat the same conditions recur in either modified or exaggerated form which frequently makes it more difficult to secure desired results. It is more desirable to attempt control by deliberately reducing the resultant distortion by reason of working out a forming procedure that takes into account known results of specific types of heat application.

While the hidden variables and the distortion which is incident to the welding operation may not be particularly troublesome, the result of this combination of conditions which is very apparent at the completion of the operation may have affected the operation during its progress through the strains set up which the machine design must be able to counteract in order that the otherwise controlled conditions are not upset.

These are the longitudinal and transverse contraction stresses which follow the weld and reach their maximum effect on the welding operation when the welded portion has cooled to the lowest degree while it is still within the control or confines of the machine. These two stresses may be of unequal value and therefore the effects of the more powerful will become evident while the other, although undetected, may be exerting an appreciable effect upon the results.

The straight butt seam is usually the operation which brings to the attention of the experimenter or the operator the forces that are released or the problems that must be surmounted in order to satisfactorily weld a seam; but the solution of problems involved in straight seam welding are only moderately helpful in successfully applying mechanical welding to a circumferential seam.

While the same forces must be reckoned with they frequently are not so pronounced but there is the additional condition of unequal heat absorption or conduction which, if it is allowed to persist, gets entirely out of control by progressively creating an effect of unequal diameter in that one edge will endeavor to rise above the other and when the starting point is reached a very decided buckle is left to indicate that something went wrong. When this occurs, it is frequently found that the transverse contraction stress has also played a part and prevented mechanical control by taking advantage of the opportunity to slip under the elevated edge, thereby aggravating the trouble.

Let us now consider a more complicated operation and one which is perhaps more frequently attempted and offers more discouragement than any other type of machine weld ordinarily attempted.

Reference is made to the circumferential weld between two deep drawn, stamped or rolled sections with straight sides, or a stamped section joined to a rolled section with straight sides or dissimilar sections with similar meeting edges. This type of operation offers difficulty by reason of the problems of holding and controlling edge position while at the same time permitting free or controlled expansion as may be necessary by reason of the form of the parts to be joined. Consider, for instance, a circumferential butt weld in a plain, fairly light sheet steel, one which must be finished to leave no trace of the weld. Circumferential expansion of the entire part must be considered, and uniformity in both meeting edge positions maintained, while in addition there occurs the extremely localized expansion which results in a bulged condition and which must be maintained uniformly in both meeting edges in order that complete and equal fusion may be produced between the opposing edges. We are compelled also to recognize the longitudinal expansion which tends to force the edges away from each other and may even prevent the unwelded opposing edges from meeting, thereby interfering with the satisfactory completion of the operation.

In this type of operation it is generally expedient to provide for modification of the heat application during the progress of the weld to counteract and control unequal expansion and uneven heating through variation in the conductivity of heat away from the welding point and thereby secure approximately uniform conditions throughout the complete operation. Every welding operation of the circumferential type is often an individual problem because of variables of different kinds and in varying degrees are encountered in similar parts. Manufacturers who by reason of their type of products utilize mechanical welding on formed parts can very considerably reduce welding costs by instituting an inspection operation when quantity warrants which will permit segregation of parts likely to be influenced by measurable variables and run such lots through the welding machine under conditions of control which will insure greater success and lower overall cost than if welded just as they happen to be selected by the operator.

Without going into detailed explanation of control and corrective methods for each individual condition, I believe the following remarks will point the way to overcome the major difficulties encountered in machine welding operations. When machine design can be of a rugged form and the absolute minimum of operating cost may not be essential, control may be effected by restraint of movement in directions which might interfere with easy operation by the average shop operator. In this case the welding speed will be sacrificed and consumption of energy will be increased and very likely weld quality will also suffer, but the result may be all that is required for the particular use for which the product is intended.

Where more economical production is required it is desirable to construct machines so that forces are more or less unrestrained but controlled within close limits and by the use of carefully trained operators secure more economical results without sacrificing quality.

In this type of design control may be divided between the component parts of the machine and the method of applying and controlling heat absorption. In other words, given a reasonable opportunity the metal in the seam edges may be allowed to move naturally and the extent of the movement to be governed by the points, at which varying amounts of heat are applied while at the welding point, sufficient heat is applied to secure satisfactory welding conditions at the desired rate of speed.

Means may also be provided for mechanical control of material movement in combination with the automatic control through graduated heat and thereby secure more positive control at an additional initial cost in machine construction.

It is well to have in mind that the introduction of heat is oftentimes the most expensive part of the welding operation cost, and advantage should always be taken of the opportunity to bring the meeting edges or the parts of the seam to a welding heat with the minimum loss of heat either into the atmosphere or through conduction or otherwise into the machine or in any manner extract heat unnecessarily from the weld region.

In closing I would like to say that it is far more economical to employ large amounts of heat in a properly designed welding machine because the welding speed increases at a far greater rate than the heating medium consumption.

Discussion of Paper by G. E. Thornton, Entitled "Giving the Weld a Chance"

By CHARLES H. JENNINGS

✦Prof. Thornton's paper was published in the February 1932 issue of the Journal of the American Welding Society. Mr. Jennings is connected with the Research Laboratories of the Westinghouse Elec. & Mfg. Co.

TESTING butt welds for tensile and fatigue properties presents many difficulties because of the difference in the physical properties of the deposited and the base metals. These difficulties are easily overcome, however, if the variables affecting the specimen designs and test results are understood.

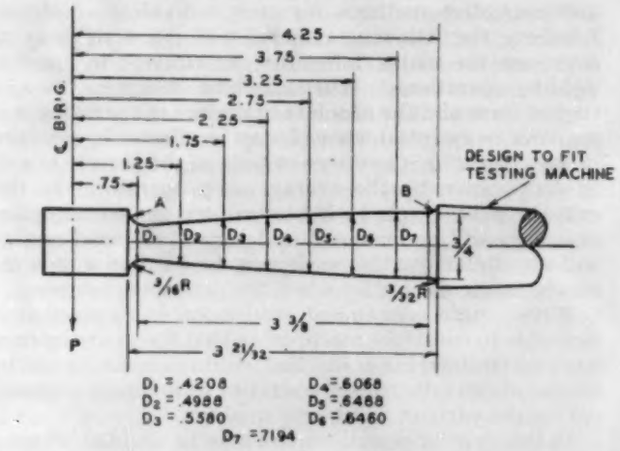

Fig. 1—Uniform Strength Cantilever Fatigue Specimen

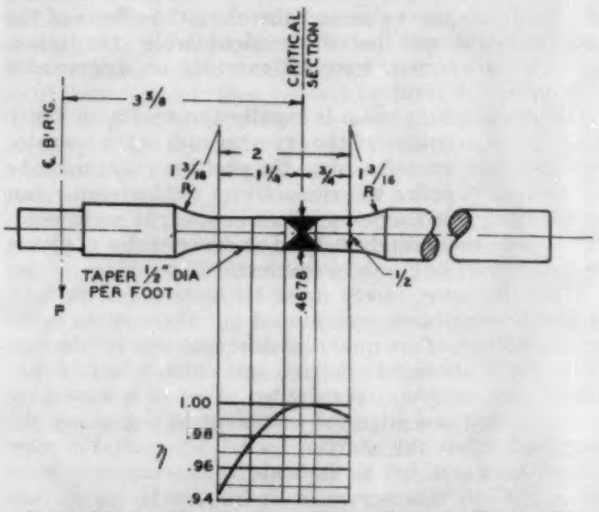

Fig. 2—McAdam Type Cantilever Fatigue Specimen Showing Stress Distribution

(Reprint from "Giving the Weld a Chance," by G. E. Thornton)

The tensile strength of butt welds made with low-carbon steel electrodes by the metallic arc process is generally higher than that of hot-rolled low-carbon steel. (This is true for welds made with bare and fluxed electrodes.) Consequently, if tests are made on such welds by using a specimen of uniform cross-section, failure will occur in the base metal and not in the weld.

The fatigue strength of butt welds made on hot-rolled low carbon steel by using low-carbon steel electrodes may or may not be higher than that of the base metal. If butt welds made with bare electrodes are tested in fatigue, failure will occur in the weld or the fusion zone at an endurance limit lower than that of the base metal.

If butt welds made with high grade fluxed electrodes are tested in fatigue, failure will generally occur in the base metal (outside the weld) at an endurance limit equal to that of the base metal.

The fact that bare electrode welds are found to be weaker than the base metal in fatigue, while they are stronger than the base metal in tension, has been attributed to the design of the specimens used in making the fatigue tests.[1] Also, resulting from this line of reasoning, a cantilever fatigue specimen of uniform strength has been proposed for butt weld tests (see Fig. 1).[1]

In the following discussion, the writer will show that the relatively low fatigue properties of butt welds made on low-carbon steel with bare low-carbon electrodes are the result of the inherent properties of the weld and not the result of the specimen design, and that the proposed uniform strength fatigue specimen is not superior to the commonly used McAdam type cantilever specimen[2] (see Fig. 2).

Considering first the effect of the specimen design on the endurance limit obtained from butt welds, the proposed cantilever specimen of uniform strength will be discussed and compared with the McAdam type cantilever specimen.

The object of a uniform strength specimen is to have a specimen of such a design that every section is subjected to the same stress. It is almost impossible, however, to design and machine a fatigue specimen so that this objective is obtained. The introduction of the sharp fillets at the ends of the specimen (points *A* and *B*, Fig. 1) cause stress concentrations. These stress concentrations cause failure to occur at the fillets, thereby destroying the purpose of the design and introducing the objectionable factor of stress concentration.

In addition to the above, it is very difficult and expersive to machine a specimen with an irregular form such as required by a uniform strength specimen (Fig. 1). Also, unless the specimen is machined exact at every point, it will not have uniform strength and the objective sought will not be obtained.

The McAdam type cantilever fatigue specimen, which corresponds to the proposed uniform strength specimen, is shown in Fig. 2. This specimen is simple in design, easy to machine and contains a so-called critical section. On both sides of the critical section, the point of highest stress, the stress gradually decreases so that at the sections where the fillets start it is reduced to such a value that there is no danger of failure occurring at these

[1] G. E. Thornton on "Giving the Weld a Chance," JOURNAL OF THE AMERICAN WELDING SOCIETY, 11, No. 2, 9 (Feb. 1932).

[2] D. J. McAdam on "Endurance of Steel Under Repeated Stress," *Chem. & Met. Eng.*, Dec. 14, 1921, p. 1081.

Fig. 3—Fractured Fatigue Specimen Showing Fatigue Cracks Around Holes

points even though a small amount of stress concentration should be present.

The stress distribution in the McAdam type specimen is plotted in Fig. 2 where "*n*" is the ratio of stress at any section to the stress at the critical section. It will be noted that for a distance of over 1 inch the stress variation is only 1%. It is evident, therefore, that this specimen has the advantages of a uniform strength specimen and is also free from erroneous results caused by fractures occurring at the base of the fillets.

When testing butt welds, the widest weld section would seldom be more than 1 inch. Consequently, the variation in stress between the weld section and the base metal section would not be more than 1 or 2%. Therefore, in the McAdam type of fatigue specimen (Fig. 2) both the weld and base metal are subjected to almost identical conditions of stress and the fact that failure occurs in the weld and at an endurance limit below that of the parent metal, is not the cause of the specimen design.

On the basis of the present knowledge, the probable cause of the low endurance limit of bare electrode welds is the small gas holes which seem to always be present. Holes and sudden discontinuities in the shape or form of stressed members cause stress concentrations. In tensile tests on ductile metals, these stress concentrations have little effect upon the ultimate strength because of the ability of the metal to yield and redistribute the stress before fracture occurs. In fatigue tests, the endurance limit is generally below the static yield point of the material. Consequently, the nature of the stress application, and the range of the stresses applied prevent the complete redistribution of stress. As a result, stress concentrations are not relieved and local fatigue cracks occur. These initial fatigue cracks spread under repeated stress applications and result in complete failure of the specimen. Figure 3 shows a fatigue fracture obtained in weld metal containing small gas holes.

Knowing that bare electrode welds contain small gas holes it is easily understood from the above discussion why they can have a very high ultimate strength and a relatively low endurance limit.[3] Welds made with high grade fluxed electrodes are free from gas holes and develop both a high tensile strength and a high fatigue strength.

In conclusion, it is sufficient to again emphasize the following points.

1. The ordinary McAdam type cantilever fatigue specimen (Fig. 2) is suitable for fatigue tests on butt welds and gives satisfactory results.
2. A uniform strength type fatigue specimen (Fig. 1) is not as satisfactory as the McAdam type specimen (Fig. 2) either from the standpoint of design or machining costs.
3. The relatively low endurance limits obtained from bare electrode butt welds is the result of the inherent properties of the welds and not of the design of the fatigue specimen.

[3] The ductility of bare electrode welds is low (about 10–15% elong. in./in.) but it is sufficient to greatly reduce the effect of stress concentrations resulting from small gas holes.

Inspection and Tests of Welding in Structures*

By F. EDER

✦This paper was presented at the April 18th Meeting of the Philadelphia Section of the American Welding Society by F. Eder of the Robert W. Hunt Company, Engineers.

IN A book written by John Langdon Davies, and entitled "Man and His Universe," one may find the following sentence, quoted from the writings of the Egyptian Monk, Cosmas Indicopleustes who lived in the sixth century A. D. and described the construction of the Universe, according to his ideas which were based on his study of the Scriptures:

> "The heavens came downward to us in four walls, which at their lower sides, are welded to the four sides of the earth beyond the ocean, each to each."

Though our conception of the Universe may differ in many details from that of the Egyptian Monk, one may infer from the above quotation that he considered welding as a proper method of connecting important parts of large structures. It is rather significant that this attitude, ascribed by us to Cosmas, is being shared at the present time by those considering welding for buildings, bridges, and similar structures, that is, it is being considered a suitable means for connecting framing, and can be properly done.

That a large number of welded buildings and bridges have been erected, and found to be satisfactory, is indicated by the result of a survey made by the AMERICAN WELDING SOCIETY during 1931, and published in the JOURNAL of that Society in the January 1932 issue. At the time of the survey there existed in the United States, 46

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bridges and 183 buildings in which welding of framing had been used. A total of 114 municipalities, including the City of New Orleans, had incorporated in their building codes provisions for welding steel building frames. This number has since been increased to 120.

Among other large cities, New York City is now considering the authorization for fusion welding in structures, in its building code, though a definite decision in this matter has not yet been rendered.

In common with other developments, a great deal of research has been conducted in order to determine the properties of welds, and it is to the credit of the welding industry that it has advanced on basis of careful research.

The safeguarding of the weld in shop and field, however, is the function of inspection offering entirely different problems from those which can be taken care of in the Laboratory. While the Laboratory method is usually done by destroying at least some of the specimens made, such procedure is not possible in shop and field inspection of the actual connections made, nor is it practicable to utilize most of the laboratory equipment in the field.

Proper inspection is of paramount importance. The safety of the structure depends in a large measure upon the welds. For consistent and proper quality of welding in shop and field, it is essential that a competent inspector supervise the welding operations systematically throughout the whole period during which welding is done.

Type of Welding Used in Buildings and on Similar Structures

With the exception of some connections made in the reinforcing systems of floors or on similar constructions in which electric resistance welding can be employed, most of the welding done in connecting framing in structures is of the fusion type. This refers both to shop and field welding. The electric arc and the gas welding processes are both being used, although at the present time the first method predominates for field welding of framing.

During the electric arc and gas welding processes, welding metal is deposited progressively in small amounts. In order to effect a satisfactory weld, such metal should become fused throughout and with the base metal, resulting in an intimate union of the parts to be joined.

It is evident that this process of depositing small amounts of molten metal lends itself well toward a satisfactory method of inspection during the welding operation. The above statement is not intended to convey the idea that surface inspection of the completed weld does not furnish some information relative to the quality of the weld, for it is possible to gain some knowledge of the workmanship of the weld by visual inspection of the completed weld. Surface inspection, when made after the weld is completed, may not, however, disclose some of the important details of the weld, such as penetration, proper fusion, and the absence or presence of gas inclusions. Surface inspection after completion is necessary. It should, however, be considered only as one part of the inspection procedure, and should not be made the sole criterion by which the quality of the weld will be judged.

The details of the processes of electric arc welding and of gas welding are quite different from one another, although the object to be attained is the same. An understanding of the requirements of inspection will be facilitated by an understanding of the principal phenomena which occur during either electric arc or gas welding.

Electric Arc Welding

During this process an arc is drawn between the parent metal and the metal electrode, or between the parent metal and the carbon electrode, depending on which of the two types of electrodes is being used.

For field welding of structures, metallic electrodes are usually employed. Either alternating or direct current welding machines are available, but, in general, direct current has been utilized for structural field welding.

Length of Arc

The proper length of the arc is one of the most important features to be considered. If the arc is too long there exists the danger of undue exposure of the molten metal which is transferred from the electrode to the metal at the weld to the atmospheric gases which may produce oxidation and embrittlement of the weld. Furthermore, an arc which is too long cannot be held as steadily as one of proper length. On the other hand, when the arc is held too short, the liquid metal which leaves the end of the electrode will bridge the gap of the arc for too long a period of time, extinguishing it, and the heat necessary for fusion and penetration will not be produced. When the arc is held at proper length, the liquid drop which leaves the electrode may also bridge the arc gap, but for a short time only, and intermittently, so that the required amount of heat is furnished by the arc to effect proper fusion and penetration. As a general rule, it may be stated that the length of the arc to be held should equal approximately the diameter of the electrode, or rather that the welder should hold the shortest possible arc, which will result in a satisfactory weld.

Manipulation of Electrodes and Arc

As indicated above, fusion welding, if properly done, results in an intimate union between the base metal and the weld metal, and between the various deposits of such metal. It is, therefore, necessary that the base metal at the welding zone be properly liquefied before it can fuse with the weld metal. This means that the liquefication of the base metal must be effected at fusion zones, and must penetrate a short distance into the base metal there. Before depositing of the weld metal starts, the base metal must be preheated by the arc.

Technique of the Welder

In order to obtain good penetration and good fusion, the welder has to follow a definite and systematic technique. Such technique is not confined to one single manner of manipulating the electrode and the arc, but there exist a number of methods which can be made to result in equally satisfactory welding. These methods differ necessarily with the various conditions under which welding is to be done, such as the shape of the joint, whether butt or fillet, the position of weld, such as overhead, vertical or horizontal, and other local conditions. The welder's technique depends also on the thickness of the parts to be joined, and on the density of the current used, as well as on the properties of the base and weld metals.

In manual metallic arc welding, such as generally used in connecting framing in buildings, a weaving motion of the electrodes is usually employed, except when beads are laid longitudinally, which, however, are usually covered by weaving over with additional layers. It is essential that the operator slows down in his motion of the electrode at the turning points and corner, otherwise good penetration will not result. The electrode is held at a leading angle of perhaps 15 degrees with a line perpendicular with the liquid pool, or else perpendicular to

the pool. A lagging angle may cause insufficient penetration.

As the maintenance, distribution and radiation of the heat of the arc are of the utmost importance, considerable skill is required to properly manipulate the electrode and adapt the welding performance to the special conditions of the job on hand.

Polarity

Various conditions of welds may require connections to be made for different polarities, that is, either the work is connected to the positive terminal of the circuit and the electrode to the negative, or vice versa. Greater heat is developed by the arc at the positive terminal than at the negative, and polarity will, therefore, depend on such factors as thickness of base metal, kind of electrode and chemical composition of the parent metal.

Crater

When connection is made for straight polarity, that is, when the electrode is connected with the negative terminal, and the base metal with the positive terminal of the circuit, the arc will cause a crater to be formed in the weld, which will be subsequently covered by the liquid metal as welding advances. At the end of each length of continuous weld, this crater will remain. Its depth which should not be less than $^1/_{16}$" provides an opportunity to measure the depth of penetration. Only one crater should be found in each continuous length of welding, such crater being left at the end of the welded length. Some welders prefer to fill up the crater.

When welding with reverse polarity, a crater in the weld will not result.

Reading of the instruments of the switchboard of the welding machine will give a good indication of proper operation of the weld, as there exist definite desirable electrical characteristics for any one set of conditions.

Current

The current required to effect proper welding will depend on the property of the electrode, on the kind and dimension of the base metal, and also on the size of the electrode, as well as on other conditions under which the weld has to be made.

Sparking and Sound

When the arc is properly manipulated it will throw a steady shower of small sparks, and in the case of bare electrodes, a regular crackling, snappy sound, with fractional intervals may be observed. An experienced welder or inspector will be able to judge, by such sound, whether the arc is properly manipulated.

It is necessary to guard against electrode and parent metal becoming too hot. If the electrode becomes too hot it should be turned end for end, or else a new electrode should be inserted in the holder, or a new start made.

Size and Contour

As the strength of a weld depends on its length, and on its throat dimension, it is necessary that all welding is made to specified size, and of the proper shape. Gages should be used, which indicate whether the weld is of the specified size, oversize or deficient in dimensions.

In a fillet weld, which is the kind of weld usually employed in structural welding, the cross section through the weld is of a triangular shape. The minimum thickness of the weld along a straight line, passing through the root, is defined as the throat of the weld. The throat according to the AMERICAN WELDING SOCIETY'S Code for Fusion Welding and Gas Cutting in Building Construction, is the distance along the line from the root to the hypotenuse, at right angles thereto, of the largest isosceles right triangle that can be constructed in a cross section of a fillet weld.

The specified throat dimension and the length of the weld, should be checked and maintained, as the strength of the connection depends, among other things, on these dimensions.

The surface of the weld should be reasonably smooth, uniform and regular in contour.

The weld metal should not overlap the base metal at the surface, nor should undercutting of the parent metal occur. Undercutting may not be always avoidable, especially when one side of the weld is vertical, while the other one is horizontal. Slight undercutting may, in some cases, be noticeable at the top of the vertical side, which is due to the fact that the liquid metal will run down due to its gravity. However, this undercutting should be visible merely as a faint line, and should not occur at the edge of the horizontal side of the fillet.

Recently shielded arc welding by covered electrode, or other means, has been extensively used, although its employment in building construction may not yet be considered an established practice.

Welding procedure and inspection must be adopted to the requirements of such processes, many of which will be similar to those for bare or slightly coated electrodes, while others may differ considerably therefrom, according to the properties of the electrodes, and the processes employed. It must be kept in mind that electric welding involves many problems of thermal, metallurgical, electrical, and mechanical nature, and that it is a rapidly advancing art.

Proper manipulation of the heat which is transmitted through the weld, and the parent metal, is one of the most essential features to be watched for. Considerable stresses may be set up by heating and cooling of the adjacent parts in the welded structure, and distortions may be caused or locked in stresses set up.

It requires skilful design, and careful operation on the part of the welder, to successfully take care of these problems.

Qualification of Welders

One of the most important features to obtain satisfactory welds, is the skill and the experience of the individual welder. It is, therefore, necessary to have each and every welder, who welds on the building or structure in question, qualified by tests. These tests should prove whether or not the welder is able to perform the class of work to be done on the particular structure. Additional qualification tests may be made to ascertain that he maintains the standard of his initial performance throughout the course of welding operation during the construction of the structure, but this should seldom become necessary as a welder who has once established his proper skill rarely deviates from his usual mechanical procedure.

The AMERICAN WELDING SOCIETY'S Code, for Fusion Welding and Gas Cutting in Building Construction has recommended certain rules for qualification tests, which should be complied with in every detail.

Surface of Parent Metal

The surface of the parent metal, where weld will be applied, should be clean, free from rust, loose scale, grease or paint. Use of linseed oil is permissible. It is further necessary that the parts to be welded are properly fitted, clamped or braced, and that all members should be properly fitted.

Inspection

The inspection of electric arc welding in buildings or in other structures should be conducted in the following manner:

Inspector to see that all welders are qualified before they are permitted to start welding on the structure under construction. It is preferable to have the inspector witness such qualification tests at the start, but if records of successful passing of such tests are certified to by responsible parties, and are obtainable, they should be submitted to the inspector, in lieu of, or in conjunction with, the initial qualification tests witnessed by him.

The inspector will supervise all welding operations by systematically watching each and every welder employed on the structure. It will not be necessary for the inspector to see each and every operation of each individual welder, but he should observe the welding of each welder at various times, to convince himself that the manual operation of the welder is satisfactory, and that the performance is kept up to the standard which the welder established by the qualification test. Should the inspector note that some of the welds are not made as carefully as others, he will require that the welder submit to new qualification tests, and he will insist that the work of each welder is of satisfactory quality, and is so maintained throughout.

When unsatisfactory welds are made, they should be melted or cut out, and replaced by new welds. It is not advisable, however, to melt out merely a small portion of one continuous weld, and replace it, as it may happen that the fusion between the old and the new portion of the weld in its length will not be entirely satisfactory.

The inspector will further insist that the surfaces to be welded are clean and that the material is properly clamped or braced for welding. He will observe the current and the voltage, as well as the manipulation of the electrode and the arc, and he will be able to judge from such observations whether or not welding is done in a satisfactory manner. The rate of travel of the arc, its position at the edge of the pool, the observable sound and sparking will also give him an indication of proper operation. In this manner he will be able to judge whether proper fusion and penetration are being effected. He will make surface inspection of the weld, will observe the crater and will see whether undercutting has occurred, and whether or not the welded metal overlaps the toe of the weld, or whether an intimate union has been accomplished. He will measure and gage the dimensions of the weld. He may require the welder to weld test pieces which he will break, and inspect the appearance of the broken surface. He will, if necessary, repeat qualification tests.

The above-outlined procedure may be termed a continuous inspection, which supervises systematically the work of all operators on the ground. It offers the great advantage of furnishing a constant picture of how the welding operation is done, and it gives an insight of the quality of the work performed, which cannot be gained by a surface inspection, after the weld has been completed.

Gas Welding

To generate the heat necessary to effect fusing of the metal in the gas fusion welded process, the combustion of acetylene gas with oxygen gas is utilized. For welding in structures these gases are supplied in special steel cylinders, which are equipped with proper regulating valves.

While using a different medium for the creation of heat, the objects to be attained by gas welding are practically the same as with arc welding.

During the gas welding process a continuous stream of metal is added to the liquid pool. If the gas stream should contain a large excess of oxygen, oxidation of the weld and gas inclusions will result. Generally speaking, the flame should be a neutral one, having neither a visible excess of acetylene nor of oxygen. Under certain conditions, however, a carbonizing flame, i.e., one containing an excess of acetylene, can be utilized, with satisfactory results.

Whether or not the proper mixture of the gases has been effected, and whether gases are supplied under suitable pressure and through clean tips, can be judged by the appearance of the flame.

A neutral mixture of gases of suitable pressure, supplied through a clean tip, is indicated by a flame having a clear, well-defined white central cone, with a round end. An unclean tip will cause the cone to assume an irregular shape, usually termed "lip cone," the end of the cone having the appearance of being bent and either pointed or constricted, in which latter case the cone assumes a bottle-like shape.

A carbonizing flame is indicated by a cone similar in appearance to the one of the neutral flame but in addition to the cone and the regular envelope flame, a third flame of nearly white color may be observed around the cone.

In an oxidizing flame the envelope flame is much shorter than in the neutral and carbonizing flame, and a feathery edge surrounds the cone.

To produce a good weld, the correct flame must be maintained throughout the whole welding operation.

Manipulation of the Torch and of the Welding Rod

The base metal is being heated by the torch, and the welding surfaces wetted, that is, the surface of the parent metal is liquefied, and the metal from the welding rod is added to the pool in liquid form. This pool presents a mirror-like surface, the liquid advancing evenly and entering the "V," or the fillet, at a uniform rate. Impurities appear as small specks in this weld, and can be floated to the surface of the weld metal by applying heat below them.

Technique of the Welder

The welder manipulates the inner cone of his flame in such manner that the pool of molten weld metal is evenly and progressively maintained. Care must be taken not to overheat the parent or the deposited metal. Various patterns of systematic motion of the torch, and of the welding rod, may result in equally satisfactory welds. As a general rule, the operator will move the tip of his welding torch around the end of the welding rod, in a semi-circular, or similar motion, preheating the parent metal, heating the end of the welding rod, causing the melted deposit to advance uniformly between the liquefied sides of the parent metal, and at regular intervals he may move his torch behind the welding rod, playing the cone on the other part of the pool, and maintaining a uniform heat throughout. Whenever necessary, he will change this motion to drive out impurities, or to suit other local conditions.

The above represents merely an outline of one method of manipulating the torch and the welding rod. It may be modified to suit the welder, and the requirements of the particular job on hand.

Our remarks made in connection with electric arc welding, and referring to size, contour, gaging, surface of the parent metal and qualifications of the welders, apply equally to gas welding.

Inspection

The inspector will convince himself that all welders on the job are qualified, following the same procedure as outlined in connection with arc welding. He will supervise all welding operations by systematically watching each and every welder from time to time. He will observe the appearance of the flame, and judge whether the mixture and pressure of the gases and the condition of the tip of the torch are satisfactory. He will watch the manipulation of the torch and of the welding rod, and will insist on good quality of the weld being maintained throughout the job. He will also insist that the surfaces of the parent metal, at welding zone, are clean, and that the various members are suitably clamped and braced. The appearance of the liquid pool will indicate to him whether or not the weld is properly made. He will measure and gage the dimensions, will make surface inspection of the weld to see that penetration at the edges has been effected, and whether or not undercutting has occurred. He may require the welder to make test welds from time to time, which can be broken or subjected to physical tests. In short, he will follow a procedure similar to the one outlined in connection with electric arc welding, which procedure is that of continuous inspection, and systematic supervision of the operation throughout the period of welding.

General

It will be necessary for the architect or engineer to incorporate in the specifications and prints, full details covering welding, so that the welder and the inspector may be guided by such instructions. Such specifications should also include requirements for the kind of welding rods to be used.

Design

It is important to keep in mind, that in order to obtain a thoroughly satisfactory welded structure, its design must be proper, and suitable for welding, and that the most careful inspection and the best skill in welding cannot render a poor design satisfactory.

Code

The code for Fusion Welding and Gas Cutting in Building Construction, formulated by the AMERICAN WELDING SOCIETY should be followed.

Tests

As previously mentioned, a great number of tests may be made to ascertain various properties of a weld. Most of these tests require laboratory equipment, and cannot be readily made in the field. One of the simplest kind of tests which can be performed in the field, consists of having the welder make welds of samples, such welds being similar to those made on the actual structure. These welds can be broken and an inspection of the surface of the fracture will give some idea of the quality of the welding. Similar specimens can be prepared for tensile tests, and as a matter of fact, such specimens are always required for the purpose of qualification tests. Other specimens should be subjected to bending tests, and the elongation caused by such bending may be measured.

X-raying of welded samples will show, among other details, the presence or absence of porosity, of gas inclusions and of fusion. Micrographs of specimens may be to show the structure of the metal in the weld, near the weld, and remote from the weld.

There have also been under consideration, tests using the magnetic properties of the weld, and the base metal, and others, which are based on comparison of specific gravity. However, with the exception of the more simple physical tests, which can be made in the field, most of these tests have to be executed in laboratories. Moreover most of these tests show merely the condition prevailing in representative samples, and not of the actual welds in the structure, and cannot be made without destroying the specimen.

There has been developed, however, by Dr. A. B. Kinzel and Mr. J. R. Dawson, a means of determining the quality of welds by an acoustic method, in which a stethoscope is employed to transmit the sound of a light blow of a hammer to the ear. This method is adaptable to inspection of welds in the field and is non-destructive.

The procedure of inspection of welds in structures suggested above requires the presence of the inspector at the building during the whole period of welding. It is a continuous inspection, permitting the inspector to see the actual welds made. Such inspection should be supplemented by random specimen tests, also by available and reliable methods of non-destructive testing.

Proper inspection of the welds in structures is of the greatest importance, and its value to the owner, engineer, contractor and the regulatory bodies cannot be over estimated.

Arc Welding Helps Save $1,000,000 on Boston Tunnel

By A. F. DAVIS

+Mr. Davis is Vice-President of The Lincoln Electric Co.

TAXPAYERS of Boston have good reason to be proud of the 31-ft. vehicular tunnel now being built in that city for it was constructed at a saving of $1,000,000 over early estimates.

The tube extends from Cross Street, Boston, to Boston Harbor, thence under the harbor to East Boston where

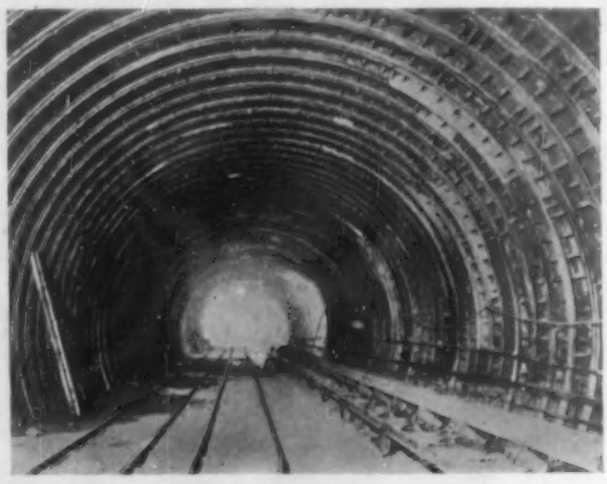


Fig. 1—The Arc Welded Steel Liner in Place. Note Rails Which Act as Stiffeners

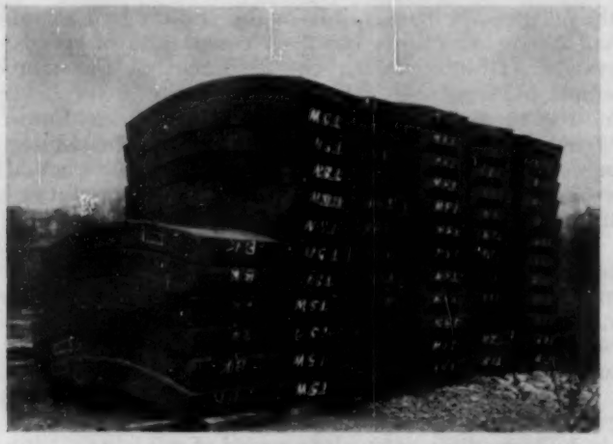


Fig. 2—Panels or Segments Ready for Installation in the Tunnel

it emerges from the ground at Porter Street. When completed the steel liner shown in Fig. 1 will be covered inside with concrete 18 in. thick. The 21 1/2-ft. roadway and ventilation equipment are being installed as the concrete is poured.

The steel liner itself is made up of rings 31 feet in diameter and 2 1/2 ft. wide. Each ring contains 11 segments or panels, each panel weighing 1250 lb. A total of 12,500 tons of steel is to be used.

Panels, as shown in Fig. 2, were fabricated by The Commercial Shearing and Stamping Company of Youngstown, Ohio. After stamping to shape, end plates and rail stiffeners were welded. The use of 3/8" covered electrodes utilizing the shielded arc process made possible extremely high welding speed. There are 132.72 miles of welding on the 19,467 panels.

After welding, templates were used to locate the 72 bolt holes in each panel, thus making them practically interchangeable.

Rings are erected following a traveling shield which is pushed forward by 32 two hundred-ton hydraulic jacks, excavating a tunnel eight inches larger in diameter than the rings.

As the shield moves forward in the tunnel, jacks are removed for the insertion of additional panels. Jacks are then shortened and replaced and when an entire new ring is in place the shield is moved forward again. Rail stiffeners in each ring absorb the thrust of the jacks.

Flanges on adjacent rings are first smeared with roofers' putty and then bolted together to make a waterproof connection. A grout mixture is blown through pipe taps in each panel to form the outer shell.

The tunnel is being constructed by the Boston Transit Commission of which Col. Thos. F. Sullivan is Chairman: Ernest R. Springer, Chief Engineer, P. L. Giering, Electrical Consultant and L. B. Howe, Designing Engineer.

Arc welding plays an important part in the construction of 28 motors which will be used to drive ventilating fans in this tunnel. The tube is longer than the Alameda tunnel in California and a foot larger in diameter than the Holland tunnel.

The Strength of Arc Welded Joints

By **FRANK RICHARD FREEMAN**

✦The following are extracts from the paper presented by Mr. Freeman before the Institution of Civil Engineers and reprinted by permission of the Council from the excerpts of minutes of Proceedings of the Institution of Civil Engineers, Volume 231, Session 1930–1931. Part 1.

IN THE investigation which is the subject of this paper a series of tests to destruction has been made on full-size specimen joints welded under workshop conditions, in order to get directly, data concerning the strength of all the types of joint likely to be met with in practice, and exhibit the effect of variation in the size and length of fillet, thickness and width of plates joined, etc.

Procedure

In order to ensure that the tests made were representative of work such as could be reproduced commercially, and at the same time to obtain effective comparative results, the following procedure was adopted.

Electrode.—"A covered mild steel" electrode No. 8 (0.160-inch diameter) and No. 10 (0.128-inch diameter) was used. This electrode is made of steel wire of the following percentage analysis:—

Carbon	Manganese	Phosphorus
0.110	0.500	0.034

It is covered with a stranding of "blue asbestos," which is a silicate of iron, with an inserted strand of aluminum wire, No. 34 S.W.G. in No. 10 and No. 31 S.W.G. in No. 8 electrode. The covering melts in the arc to form a flux and prevent oxidation of the weld-metal. The slag hardens on cooling and is removed by chipping and wire-brushing.

The "uranium" electrode is similar to the "mild steel" electrode, but the wire has a much higher manganese content, as the following percentage analysis shows:—

Carbon	Manganese	Phosphorus
0.110	3.130	0.046

Material.—All specimens were cut from plates rolled at the firm's Redcar mills, specimens of the same thickness being all from one plate and all plates from the same cast. The material is basic open-hearth steel of 28–33 tons per square inch breaking-strength, rolled to British Standard Specification No. 15. The chemical analysis of the plates was as follows:—

Carbon	Manganese	Sulphur	Phosphorus
0.20	0.50	0.04	0.03

Several standard test-pieces were broken, with the following average results:—

Plate Thickness, Inch	Ultimate Strength, Tons per Square Inch	Elongation on 8 Inches, Per Cent
1/4	31.5	27
3/8	29.4	25
1/2	29.6	28
5/8	30.2	27
3/4	30.9	30

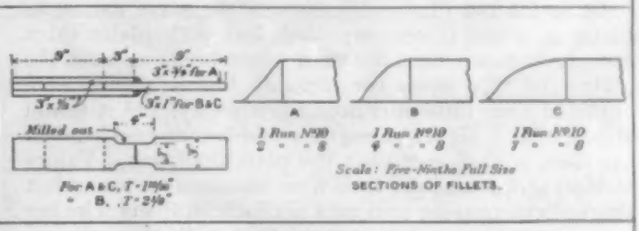
All specimens were tested in the direction of rolling.

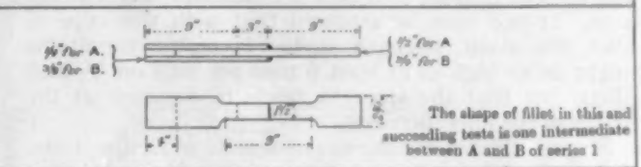
All plates (except those more than 3/4 inch thick) were sheared to size and received no other preparation.

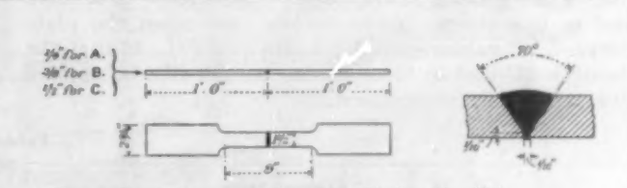
Table I

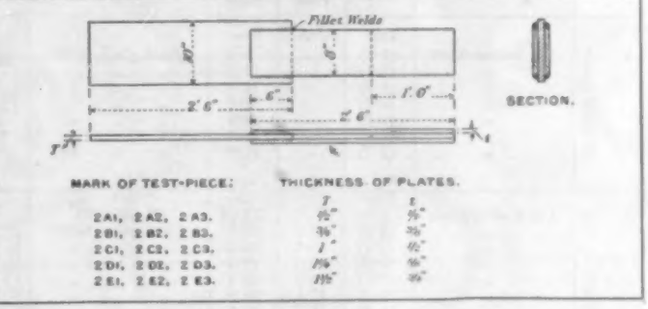
No. of Test.	Size and Type of Weld.	Average Ultimate Load per Inch of Fillet.	Average Yield Stress per Square Inch of Plate.	Average Ultimate Stress per Square Inch of Plate.	Type of Failure.
		Tons.	Tons.	Tons.	
1A 1	¼-inch tension fillets	11·2	..	(22·5)	Welds
2	,,		..	(22·3)	,,
3	,,		..	(22·5)	,,
1B 1	¼-inch tension fillets	12·6	..	(25·0)	Welds
2	,,		..	(25·1)	,,
3	,,		..	(25·4)	,,
1C 1	¼-inch tension fillets	14·1*	..	(29·1)	Welds
2	,,		..	(27·3)	,,
3	,,		..	(24·8)	,,
101 A1	¼-inch tension fillets	6·8	..	(27·3)	Welds
2	,,	6·1	..	(24·5)	,,
3	,,	6·8	..	(27·3)	,,
4	,,	6·7	..	(27·7)	,,
B1	⅜-inch tension fillets	8·2	..	(21·8)	Welds
2	,,	8·2	..	(21·8)	,,
3	,,	7·6	..	(20·3)	,,
4	,,	8·0	..	(21·5)	,,
102 A1	¼-inch butt	..	..	27·2	Weld
2	,,	..	..	25·4	,,
3	,,	..	..	26·2	Plate
4	,,	..	..	25·9	Weld
B1	⅜-inch butt	..	..	26·9	Weld
2	,,	..	..	26·4	,,
3	,,	..	..	27·4	Plate
4	,,	..	..	27·2	,,
C1	½-inch butt	..	..	28·2	Weld
2	,,	..	..	29·0	,,
3	,,	..	..	28·3	,,
4	,,	..	..	28·8	,,
2A 1	¼-inch shear fillets	3·1	17·5	(18·6)	Welds failed
2	,,	3·3	19·5	20·0	Welds and plates failed
3	,,	3·0	..	18·2	Welds failed
2B 1	⅜-inch shear fillets	(4·9)	13·6	15·7	⅜-inch plate failed
2	,,	(4·8)	17·0	19·3	⅜-inch plates failed
3	,,	(5·0)	17·5	20·0	,, ,, ,,
2C 1	½-inch shear fillets	6·5	..	(19·4)	Welds failed
2	,,	6·0	..	(17·9)	,, ,,
3	,,	7·0)	..	21·2	½-inch plates failed
2D 1	⅝-inch shear fillets	7·4	15·4	(17·7)	Welds failed
2	,,	(7·6)	15·5	18·1	⅝-inch plates failed
3	,,	(7·5)	16·6	17·9	,, ,, ,,
2E 1	⅝-inch shear fillets	(8·2)	..	16·4	⅝-inch plates failed
2	,,	(8·6)	..	17·2	,, ,, ,,
3	,,	(8·9)	..	17·8	,, ,, ,,

DETAILS OF TEST-PIECES.






These small test-pieces were cut from plates 12 inches wide, which had been welded continuously across their width; thus Nos. 1 and 4 are the ends of the weld, and Nos. 2 and 3 the centre



*1C 3 is disregarded as being a freak failure, due to unequal gripping in machine

Welding.—Care was taken to ensure that the welding of specimens was done under ordinary commercial conditions, without any special devices to improve the quality of the work beyond what could be reckoned upon as the normal practice of a well-managed shop. All the welding was done with standard equipment at Redcar works. The welder employed (Mr. W. Brunskill) had previously been engaged on repair welding of plant at Redcar. He is a careful and conscientious worker, with a fairly wide experience of welding. All the welds were run "on the flat," that is, the welder kept the electrode above the work with the plates lying flat. Direct current was employed, with an open-circuit voltage of 80 volts. The current varied between 80 and 100 amperes for the No. 10 electrode and between 120 and 130 amperes for the No. 8 electrode.

The ends of longitudinal fillet welds were chipped flush with the ends of the plates.

Longitudinal Shear Fillets

Series 2 (Table I) shows the strength of longitudinal fillets in shear, the tests being made on fillets 6 inches long and plates 8 inches wide, ranging in thickness from ¼ to ¾ inch. The weld did not fail in all cases in these tests, but the values given for breaking-strength may, at least, be assumed, and it is possible that higher values could be shown to be permissible. Tests from later series on ⅜-inch plates show that values of about 4.8 tons per inch can be confidently relied upon as a practical breaking-strength for a ⅜-inch fillet. For ¼-inch and ½-inch fillets the values are approximately proportional to the size of fillet, and rather less than proportional for larger fillets.

Series 3 (Table II) comprised tests on ⅜-inch fillet welds of various lengths, but all on the same width of plate, namely 8 inches; all these tests give results exceeding the 4.8 tons per inch previously mentioned. In these tests the plates failed and not the weld.

In Series 4 and 5 (Table II) the tests in Series 3 were repeated on plates, respectively, 4 inches and 12 inches wide; again the plate failed in almost all cases, but at a figure where the weld-strength exceeded 4.8 tons per inch.

In Series 6 (Table II) welds were made on plates 8 inches wide by ⅜ inch thick on one side of the weld and of various thicknesses on the other side. In most cases again the plate failed, but with a weld-strength exceeding 4.8 tons per inch.

From these tests, within the range over which the specimens were tested (which covered all likely practical

joints), it appears safe to assume for $^3/_8$-inch longitudinal fillets in shear a reliable breaking-strength of 4.8 tons per inch, irrespective of the width between the two fillets, the relative thickness of the two pieces joined and the length of the fillet.

In Series 106 (Table II) tests of the same nature as Series 3, 4 and 5 were repeated, but with plates thick enough to ensure that the weld would break and not the plate. In this series considerably higher values were obtained than those mentioned previously, and it would appear that a higher strength would be admissible when the fillet is shallower than the plate-thickness. Values as high as 6.1 tons per inch were obtained on somewhat short fillets, ranging to 5 tons per inch on fillets 9 inches long. It can thus be assumed that with this type of fillet the shear strength under favorable conditions might be as high as at least 6 tons per inch on $^3/_8$-inch fillets, but that the strength tends to diminish as the length of the fillet increases.

Series 7 (Table II) shows the results of similar tests, the specimen being in compression instead of in tension, and in this series, except in one case when the plate buckled, all values exceed 5.8 tons per inch, so that the strength allowed in tension may confidently be applied to specimens in compression.

Series U 2 (Table VI) consisted of tests of longitudinal fillet welds made with "uranium" electrode, the strength being approximately the same as that for "mild steel" electrode.

Conclusions Regarding Longitudinal Fillet Welds.—For fillet welds up to $^1/_2$ inch deep and of the standard shape described, a breaking-strength per inch may be assumed proportional to the depth of the fillet, the figure of 4.8 tons per inch for $^3/_8$-inch fillets being used. These figures would be as follows:—

Inch	Tons per Inch	Inch	Tons per Inch	Inch	Tons per Inch
$^1/_4$	3.2	$^3/_8$	4.8	$^1/_2$	6.4

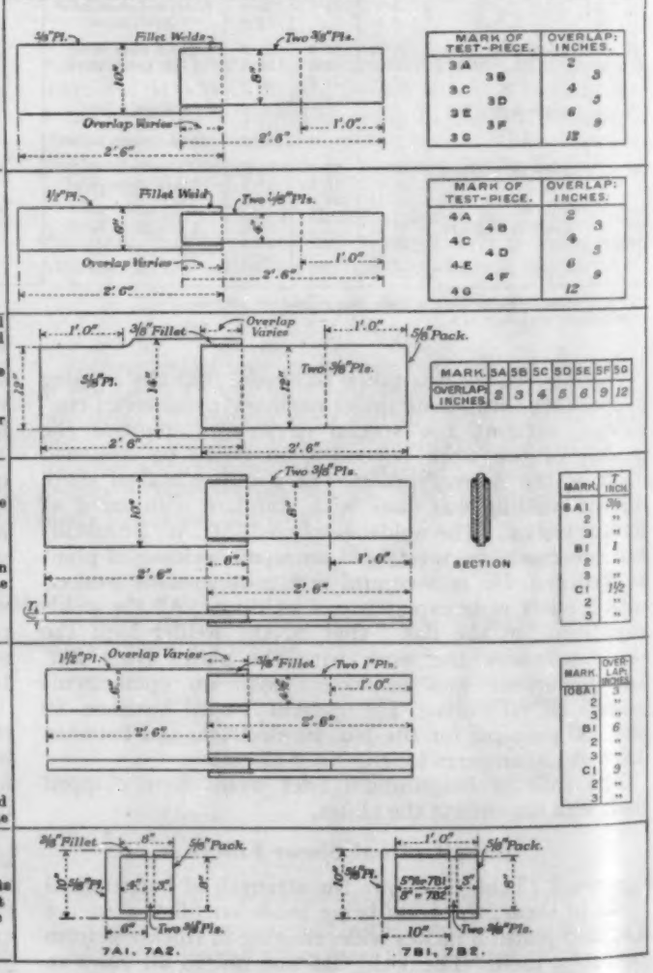
For larger fillets it would appear to be necessary to reduce the allowable load in proportion to the depth, but enough tests have not been made to arrive at the proper reduction to be made. Fillets larger than $^1/_2$ inch, however, would rarely be used in practice at their full strength.

These values are reliable for any probable relative thicknesses and widths of connected plates and lengths of weld, and apply with a higher factor of safety to fillets on plates thicker than the depth of the fillet.

It would appear that there is some falling-off in

Table II

No. of Test.	Size and Type of Weld.	Average Ultimate Load per Inch of Fillet.	Average Yield Stress per Square Inch of Plate.	Average Ultimate Stress per Square Inch of Plate.	Type of Failure.	DETAILS OF TEST-PIECES.
		Tons.	Tons.	Tons.		
3 A	¾-inch shear fillets	(5·1)	..	6·8	¾-inch plates failed	
B	,,	(5·1)	..	10·2	,, ,, ,,	
C	,,	(5·3)	..	14·1	,, ,, ,,	
D	,,	(5·1)	..	17·0	,, ,, ,,	
E	,,	(4·9)	..	19·6	,, ,, ,,	
F	,,	(3·4)	..	20·6	,, ,, ,,	
G	,,	(2·7)	..	21·8	,, ,, ,,	
4 A	¾-inch shear fillets	5·0	..	(13·3)	Welds failed	
B	,,	(5·2)	16·7	20·7	¾-inch plates failed	
C	,,	(4·4)	17·0	23·4	,, ,, ,,	
D	,,	(3·6)	17·3	23·6	,, ,, ,,	
E	,,	(2·7)	16·7	22·0	,, ,, ,,	
F	,,	(2·0)	17·7	24·0	,, ,, ,,	
G	,,	(1·4)	16·7	22·2	,, ,, ,,	
5 A	¾-inch shear fillets	(6·1)	4·3	5·4	[of weld ¾-inch plate tore at end	
B	,,	5·2	6·0	(6·9)	Welds failed	
C	,,	5·2	8·0	(9·3)	Weld failed. Plates tore	
D	,,	5·2	10·2	(11·7)	,, ,,	
E	,,	(5·2)	11·3	14·0	As 5A	
F	,,	(4·4)	13·1	17·4	,, [shoulder	
* G	,,	(3·9)	14·8	25·1	¾-inch plate tore at	
6A 1	¾-inch shear fillets	(5·1)	17·2	20·4	¾-inch plate tore	
2	,,	(4·9)	17·2	19·7	¾-inch plate tore, ¾-inch	
3	,,	(5·1)	17	20·2	As 6A 1 [plate broke	
6B 1	¾-inch shear fillets	(4·9)	17	19·7	As 6A 1	
2	,,	(4·9)	17	19·7	,,	
3	,,	(5·0)	17	20·0	¾-inch plate tore, then [one weld broke	
6C 1	¾-inch shear fillets	(5·0)	17	19·8	As 6A 1	
2	,,	(4·9)	16·7	19·6	,,	
3	,,	(4·9)	16·7	19·7	As 6B 3	
106A 1	¾-inch shear fillets	5·8	..	(7·8)	Welds failed	
2	,,	5·8	..	(7·8)	,, ,,	
3	,,	6·1	..	(8·2)	,, ,,	
106B 1	¾-inch shear fillets	6·0	..	(16·1)	Welds failed	
2	,,	5·5	12·2	(14·8)	,, ,,	
3	,,	5·8	12·4	(15·5)	,, ,,	
106C 1	¾-inch shear fillets	5·2	12·4	(20·9)	Welds failed	
2	,,	5·3	11·3	(21·1)	,, ,,	
3	,,	5·9	12·4	20·1	Welds one side and [1-inch plate	
7A† 1	¾-inch shear fillets	5·8	..	(15·5)	Welds failed	
2	,,	5·8	..	(15·6)	,, ,, [gap in ¾-inch plate	
7B 1	¾-inch shear fillets	(3·6)	..	19·3	¾-inch plates buckled at	
2	,,	5·5	..	(18·3)	Welds failed one side	


MARK OF TEST-PIECE.
OVERLAP: INCHES.
3A 3B 3C 3D 3E 3F 3G
2 3 4 5 6 9 12
4A 4B 4C 4D 4E 4F 4G
2 3 4 5 6 9 12
MARK. 5A 5B 5C 5D 5E 5F 5G
OVERLAP: INCHES. 2 3 4 5 6 9 12
MARK. T INCH
6A1 2 3 B1 2 3 C1 2 3
SECTION
MARK. OVERLAP: INCHES.
106A1 2 3 B1 2 3 C1 2 3
7A1, 7A2.
7B1, 7B2.

* ¾-inch plate

† Two 8-inch by ¾-inch plates

Table III

No. of Test.		Size and Type of Weld.	Average Ultimate Load per Inch of Fillet.	Average Yield Stress per square inch of Plate.	Average Ultimate Stress per Square Inch of Plate.	Type of Failure.	DETAILS OF TEST-PIECES.
			Tons.	Tons.	Tons.		
8A	1	¼-inch tension fillets	4·4	..	(17·5)	Weld failed	
	2	,,	4·1	..	(16·5)	,,	
	3	,,	4·3	..	(17·2)	,,	
8B	1	⅜-inch tension fillets	6·7	..	(17·9)	Weld failed	
	2	,,	7·4	16·3	(19·8)	,,	
	3	,,	6·3	16·8	(16·8)	,,	
8C	1	½-inch tension fillets	9·4	17·25	(18·8)	Weld failed	
	2	,,	8·6	15·0	(17·2)	,,	
	3	,,	10·0	15·0	(20·0)	Weld and 1-inch plate broke	
8D	1	⅝-inch tension fillets	9·9	12·1	(15·9)	Welds failed	
	2	,,	9·4	14·2	(15·1)	,,	
	3	,,	10·4	14·4	(16·7)	,,	
8E	1	¾-inch tension fillets	11·8	15·8	(15·7)	Welds failed	
	2	,,	11·4	12·8	(15·2)	,,	
	3	,,	12·6	12·8	(16·8)	,,	
R8	B1	⅜-inch tension fillets	7·2	17·1	(19·2)	Welds failed	
	2	,,	6·6	17·6	(17·6)	,,	
	3	,,	7·0	17·5	(18·7)	,,	
10S	B1	⅜-inch tension fillets	8·6	20·0	(23·0)	Welds	
	B2	,,	8·6	20·8	(22·8)	,,	
	B3	,,	8·5	21·0	(22·6)	,,	
11	C1	⅜-inch double tension fillets	7·6	..	(17·3)	Welds	
	C2	,,	(7·1)	..	16·1	Plate	
	C3	,,	7·9	15·4	(18·0)	Welds	

* E1 and 2 were welded by a different welder

strength per inch for long fillets as against short fillets, but not to an extent sufficient to affect the figures of strength given. Possibly further tests would enable some higher values to be assumed, if an allowance be made for this falling-off in strength for long fillets as compared with short fillets.

In Series 3, 4 and 5 the plates failed at an extremely low average stress, and, from the nature of the failure, there is no doubt that that was due to the high edge stress set up in the plate by this type of weld. In order to obtain a plate-strength up to, say, 20 tons per square inch—that is, a value exceeding the yield-point of the plate—it is necessary to use with 8-inch by $^3/_8$-inch plate a weld 6 inches long; with 4-inch by $^3/_8$-inch plate a weld 3 inches long; and with 12-inch by $^3/_8$-inch plate a weld more than 9 inches long. If longitudinal fillets are used alone their length should therefore be at least three-quarters of, and preferably equal to, the width of the plate joined. Longitudinal fillets would, however, rarely be used in practice at their full strength except in combination with transverse fillets.

It is interesting to follow this characteristic of longitudinal fillet welds, as exemplified in the results of Series 3, 4 and 5, a little further. The tabulated results of these tests show that the usual type of failure, independent of the width of the plate, is a splitting or tearing of the plate at the end of the longitudinal fillet weld. But, although the actual fracture of the joint has occurred in the plate, it is evident that in many cases this fracture has been precipitated by the failure of the weld. Thus, in tests 3 A, B, C, D, E, 4 A, B and 5 A, B, C, D, E, the $^3/_8$-inch fillets attained their ultimate strength of about 5 tons per inch. Initial failure of the weld is believed to have occurred at this stress, causing a redistribution of stress in the plate, with high intensities at the edges; and doubtless this high edge intensity caused the plate to fail by tearing.

In the other tests of these series, where longer fillets were used, the failure occurred by tearing of the plate in the same way, but at a stress per inch of weld below its ultimate strength. In these cases, namely, 3 F, G, 4 C, D, E, F, G and 5 F, G, fracture occurred at a stress in the plate of 20 to 22 tons per square inch, and even where a very long weld was used, as in 4 G, no greater strength of the plate was obtained. Thus, it appears that the yielding of the plate at a stress of about 20 tons per square inch similarly causes a redistribution of stress which starts the tearing at the edges.

The joint fails, therefore, at a load corresponding to either (1) a stress of about 5 tons per linear inch of fillet, or (2) a stress of about 20 tons per square inch in the plate, whichever is the lower.

It would appear probable that this stress-redistribution only takes place near the yield-point of either the plate

or the weld, and, if that is the case, it has no influence on the distribution of stress within the elastic limit, and should not, therefore, be too greatly emphasized in deducing safe working-stresses.

Transverse Fillets

In Series 8 (Table III) tests were made of fillets of various sizes connecting plates of the same thickness as the depth of the fillet. The results are not nearly so consistent as those for longitudinal fillets. As in the case of the longitudinal fillets, the results are not so good proportionately for large fillets as for small fillets.

In Series 11 (Table III) similar tests were carried out on double transverse fillets, with a $^{7}/_{8}$-inch plate and a $^{3}/_{8}$-inch fillet, and considerably higher strengths were obtained. There is no doubt that, as with longitudinal fillets, it is desirable to use a fillet thinner than the plates joined.

In order to elucidate the inconsistency of the foregoing tests, test Series 101 (Table I) was made on $^{1}/_{4}$-inch and $^{3}/_{8}$-inch fillets on prepared specimens machined to the shape shown in Table I. These tests gave more constant values, greatly exceeding those in Series 8, namely:—

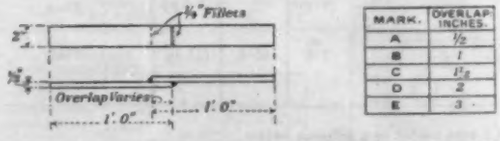
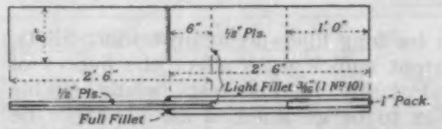
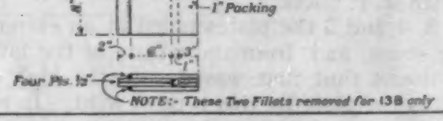
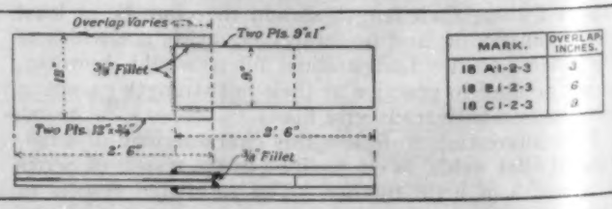
For $^{1}/_{4}$-inch fillets, 6.8, 6.1, 6.8 and 6.7 tons per inch.
For $^{3}/_{8}$-inch fillets, 8.2, 8.2, 7.6 and 8.0 tons per inch.

From these test results it would appear that the true strength of transverse fillets is considerably affected by their practical application to large-scale joints.

The inconsistency in the results of transverse-fillet tests on wide unprepared specimens may perhaps be explained in the following manner. In testing wide plates there is necessarily some inequality in the distribution of stress across the section, and frequently an actual external moment, due to eccentrically-applied load, producing a similar effect in unequal distribution of stress. In a joint where one plate is joined to two others by single transverse welds, let it be assumed that there is present a moment M. The stress per inch of weld, due to this moment, at each edge of the plate would be $6\ M/W^2$, where W denotes the width of the plate. In a joint with longitudinal welds of the same width and thickness and total length of weld (a weld-length of $^{1}/_{2}\ W$ at each side), the stress per inch induced by the moment M would be only $2\ M/W^2$. Thus, the effect of any moment existing tends to produce a stress very much higher in single transverse welds than it does in a double longitudinal weld. However, in a double transverse weld the moment would tend to be partly taken up in the same manner as in a double longitudinal weld, by shearing along the length of each of the welds, as is exemplified by the results of test Series 11 C (Table III).

This high intensity of stress, however, does tend to exist at the ends of all transverse fillet welds, and it is

Table IV

No. of Test.		Size and Type of Weld.	Average Ultimate Load per Inch of Fillet.	Average Yield Stress per Square Inch of Plate.	Average Ultimate Stress per Square Inch of Plate.	Type of Failure.	DETAILS OF TEST-PIECES.
			Tons.	Tons.	Tons.		
111	A	½-inch double tension fillets on ½-inch plate	(4·8)	..	19·3	Plate failed	
	B	,,	5·5	..	(22·0)	Weld failed	
	C	,,	5·6	..	(22·4)	,,	
	D	,,	5·8	..	(23·4)	,,	
	E	,,	5·9	..	(23·5)	,,	
12	A*	½-inch double tension fillets	11·1	17·25	(22·2)	Welds failed	
	B	,,	10·4	17·5	(20·8)	One weld and plate broke	
	C	,,	(10·6)	17·5	21·2	Plates broke	
13	A	½-inch fillets in compression	(5·4)	..	21·5	Plates buckled	
	B	,,	8·3	13·8	(16·5)	Welds failed	
17	A	⅞-inch tension fillets	4·9	..	(19·7)	Welds failed	Similar to 101A but with ⅜" Fillets instead of ¼"
	B	,,	5·3	..	(21·3)	,,	
	C	,,	4·2	..	(16·9)	,,	
18	A1	Combined tension and shear weld	6·7	15·1	(17·8)	Welds failed	
	2	,,	6·7	15·3	(17·8)	,,	
	3	,,	6·6	15·5	(17·6)	,,	
	B1	Combined tension and shear weld	5·8	15·1	(19·2)	Welds failed	
	2	,,	6·3	15·5	(21·1)	Welds and ½-inch plate failed	
	3	,,	(6·3)	15·3	20·9	Both 1-inch plates failed	
	C1	Combined tension and shear weld	5·8	15·0	23·2	Welds and 1-inch plate failed	
	2	,,	5·7	15·3	22·7	,,	
	3	,,	5·5	15·4	(21·9)	Welds failed	

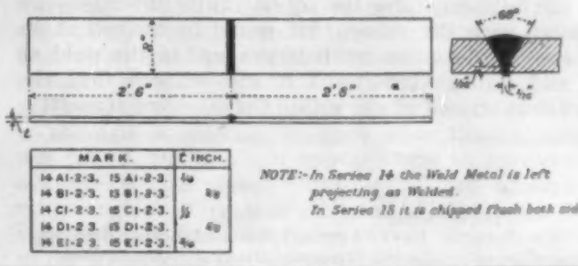
MARK.	OVERLAP INCHES.
A	½
B	1
C	1½
D	2
E	3

MARK.	OVERLAP INCHES.
18 A1-2-3	3
18 B1-2-3	6
18 C1-2-3	9

* Light fillet not included in length.

Table V

No. of Test.	Size and Type of Weld.	Average Yield Stress per Square Inch of Plate.	Average Ultimate Stress per Square Inch of Plate.	Type of Failure.	DETAILS OF TEST-PIECES.
		Tons.	Tons.		
14 A1	¼-inch butt	18·25	18·5	Weld failed	
2	,,	16·5	17·0	Weld tore at edges, then plate tore at centre	
3	,,	18·5	21·5	Weld failed	
B1	⅜-inch butt	15	16·5	Weld failed	
2	,,	15·7	18·2	,,	
3	,,	15·3	18·3	,,	
C1	½-inch butt	16·25	19·4	Weld and plate broke	
2	,,	15·75	19·3	Weld failed	
3	,,	15·5	22·6	,,	
D1	⅝-inch butt	15	21·6	Weld failed	
2	,,	15	20·4	,,	
3	,,	15·8	20·4	Plate broke clear of weld	
E1	¾-inch butt	14·3	15·8	Weld failed *	
2	,,	13·8	15·0	,,	
3	,,	..	16·4	,,	
15 A1	¼-inch butt	18·5	21·7	Weld failed	
2	,,	18·5	18·8	,,	
3	,,	18·5	20·5	,,	
B1	⅜-inch butt	16	17·8	Weld failed	
2	,,	15	15·8	,,	
3	,,	15·3	18·5	,,	
C1	½-inch butt	15·75	20·0	Weld failed	
2	,,	16·5	20·5	,,	
3	,,	15·75	17·0	,,	
D1	⅝-inch butt	14·8	18·6	Weld failed	
2	,,	15	20·0	,,	
3	,,	14·8	21·9	,,	
E1	¾-inch butt	14·3	14·9	Weld failed †	
2	,,	14·2	16·0	,,	
3	,,	14·7	20·4	,,	
R14 E1	Butt weld	12	15·9	Weld failed	
2	,,	12·7	15·9	,,	
3	,,	13	15·2	Plate broke clear of weld	
R15 E1	Butt weld	14·2	16·3	Weld failed	
2	,,	13·7	16·0	,,	
3	,,	13·5	15·8	,,	
		Ultimate Shear Stress in Rivets.			
16	Rivet weld	19.2 Tons per Square Inch.	15·3	Rivets sheared	


2'.6"
2'.6"
60°
MARK. C INCH.
14 A1-2-3. 15 A1-2-3. ¼
14 B1-2-3. 15 B1-2-3. ⅜
14 C1-2-3. 15 C1-2-3. ½
14 D1-2-3. 15 D1-2-3. ⅝
14 E1-2-3. 15 E1-2-3. ¾
NOTE:- In Series 14 the Weld Metal is left projecting as Welded.
In Series 15 it is chipped flush both sides.

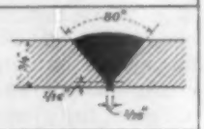
See above

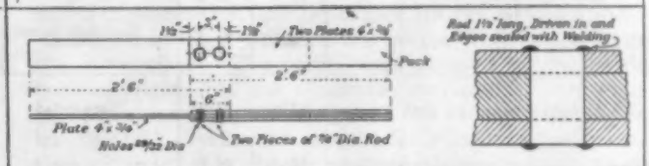
All butt welds were welded from one side only with the two pieces laid flat, without any initial tilt, to eliminate distortion. The pieces, therefore, showed a change in angle of about 2 degrees at the weld.
The ends of the welds were given no special treatment by chipping, etc., being left just as welded.

NOTE:- Otherwise as 14 above.

No improvement, due to the wider V, is observed.

NOTE:- Otherwise as 15 above.





* Insufficient penetration of 1st run. Repeated with wider V, see R14

† Insufficient penetration of 1st run. Repeated with wider V, see R15

at that point that the weld is likely to be weakest. In practice, therefore, it would appear desirable never to use at full working-stresses single transverse fillets alone, and to use double transverse fillets alone only when the ends are returned slightly to provide two short longitudinal fillets. To test the effect of these, test Series 108 (Table III) was made, the specimens being similar to those in Series 8, but having longitudinal fillets ½ inch long returned at the corner of each transverse fillet. These tests indicate that, after deducting the value of the longitudinal fillets, the strengths exceed those for transverse fillets without returned ends, as shown in the following table:-

Strength of Welds in Series 108	Value of Short Longitudinal Fillets at 5 Tons per Inch	Value of Transverse Fillets Alone in Series 108	Value of Transverse Fillets in Series 8	Strength per Inch of Transverse Fillet in Series 108 (Strength of Longitudinal Fillets Deducted)
Tons	Tons	Tons	Tons	Tons
138	10	128	107	128 ÷ 16 = 8.0
137	10	127	119	127 ÷ 16 = 7.9
136	10	126	101	126 ÷ 16 = 7.9

The strengths per inch in the last column should be compared with those in Series 101 B, namely, 8.2, 8.2, 7.6 and 8.0 tons.

Series R 8 (Table III) was made with specimens having hinged ends, as it was considered possible that eccentricity was introduced in the test owing to fixity of the specimen in the grips of the machine. No improvement was, however, obtained, the results merely confirming those in Series 8.

In Series 13 (Table IV) tests were made on transverse fillets, the load being applied in compression instead of in tension. Although the plates buckled, it appears that the figures derived from the results of tests in tension may be considered safe for compressive stresses.

In Series U 8 (Table VI) tests were repeated with "uranium" electrode and gave results which confirm, but are not superior to, those obtained with "mild steel" electrode.

Conclusions Regarding Transverse Fillet Welds.—Transverse fillets, if used alone, should preferably be finished by returning short longitudinal fillets of, say, one-tenth of the length of the fillet itself; or, if returned ends are not used, a similar fraction of the length of the fillet at each end should be neglected in calculating the strength.

The following breaking-strengths of fillets in tension can be counted upon:—

Inch	Tons per Inch	Inch	Tons per Inch	Inch	Tons per Inch
1/4	5.4	3/8	8.0	1/2	10.7

Values considerably exceeding those mentioned were obtained for 1/4-inch fillets and also in Series 1 for 1/2-inch fillets.

In the following table the actual values in Series 8 are compared with the values that would be arrived at on the basis of calculation when 10 per cent of the weld at each end is neglected; and it will be seen that the values thus arrived at are within the observed strengths.

Size of Fillet	Total Length of Fillet	Length with 10 Per Cent Deducted at Each End	Assumed Strength per Inch	Total Assumed Breaking-Load	Actual Breaking-Loads from Series 8
Inch	Inches	Inches	Tons	Tons	Tons
1/4	16	12.8	5.4	69	70, 66, 69
3/8	16	12.8	8.0	102	107, 119, 101
1/2	16	12.8	10.7	137	150, 138, 160

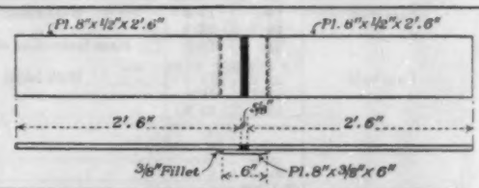
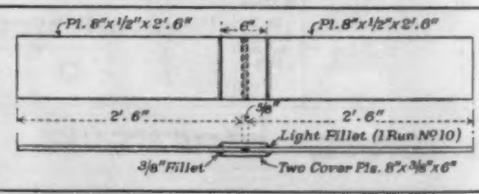
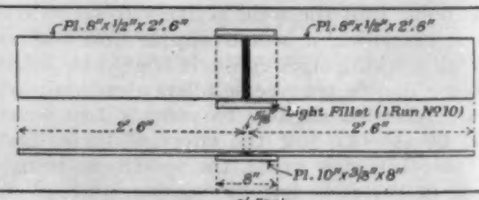
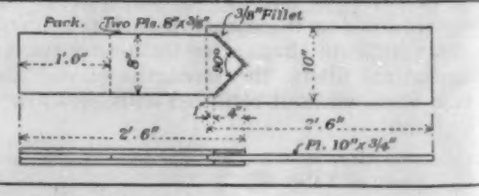
Butt Welds

In Series 14 (Table V) tests were made with the weld left as finished by the operator, and in Series 15 (Table V) a similar series of specimens was tested with the projecting portion of the weld chipped off flush. These gave substantially similar results, namely, a stress in the weld ranging from a minimum of 14.9 tons to a maximum of 22.6 tons per square inch. Only four values out of the thirty in these two series are, however, lower than 16 tons per square inch, and these are only in the thickest weld, namely, 3/4 inch. The 3/4-inch welds were welded only from one side, and it is usually recommended that such thick welds should be done from both sides. It is proposed, therefore, to neglect the figures for 3/4-inch welds. The average values per square inch of plate were as follows:—

Series 14	19.5 tons
Series 15	19.3 tons

In Series U 14 (Table VI) these tests were repeated on 3/8-inch thick plates with "uranium" electrode, giving results for the ultimate stress in the weld of 24.6, 21.3 and 20 tons per square inch, which are substantially better than those obtained in Series 14. It is probable from the inconsistency of these tests and the low stresses obtained in some of them, that somewhat similar con-

Table VI

No. of Test.	Size and Type of Weld.	Average Ultimate Load per Inch of Fillet.	Average Yield Stress per Square Inch of Plate.	Average Ultimate Stress per Square Inch of Plate.	Type of Failure.	DETAILS OF TEST-PIECES.
		Tons.	Tons.	Tons.		
U19 A	Single strap butt joint	..	16·5	25·2	Plate failed	
B	,,	..	16·0	27·0	,,	
C	Butt weld	..	15·3	21·2	Butt weld failed	
U20 A	Double strap butt weld	..	17·0	22·0	Plate failed	
B	,,	..	15·8	24·0	,,	
C	Butt weld	..	14·8	21·2	Butt weld failed	
U21 A	Single strap butt weld	..	14·0	20·7	Plate failed	
B	,,		14·7	20·2	,,	
C	,,	..	15·2	21·0	,,	
U22 A	3/8-inch combined weld	5·4	17·0	(20·5)	Welds failed	
B	,,	5·7	17·7	(21·5)	,,	
C	,,	6·3	17·0	(23·6)	,,	
U14 B1	3/8-inch butt	..	17·0	24·6	Weld	Similar to 14 B.
2	,,	..	17·3	21·3	,,	
3	,,	..	15·3	20·0	,,	
U8 B1	3/8-inch tension fillets	6·6	13·4	(17·6)	Welds	Similar to 8 B.
2	,,	7·0	14·0	(18·6)	,,	
3	,,	7·4	14·3	(19·8)	,,	
U2 B1	3/8-inch shear fillets	(5·0)	14·3	19·8	Plates tore	Similar to 2 B.
2	,,	(4·9)	14·0	19·5	,,	
U106 B1	3/8-inch shear fillets	6·5	13·3	(17·3)	Welds	Similar to 106 B.
2	,,	6·3	13·1	(16·9)	,,	
3	,,	6·4	13·7	(17·0)	,,	

ditions exist in a butt weld to those dealt with in a transverse weld in tension; that is, there is a tendency toward a high intensity of stress at the ends, where the weld tends to be weakest.

In order to find the true strength of a butt weld, test Series 102 (Table I) was prepared, the specimens being machined and shouldered and of small section. (They were made from one wide bar cut into several specimens and welded with "mild steel" electrode.) The ultimate stress in these ranges between a minimum of 25.4 and a maximum of 29 tons per square inch, with an average of 27.2 tons per square inch. It is, thus, clear that the ultimate strength obtainable on small specimens cannot nearly be relied on with specimens of practical size, and it would seem probable that the explanation given in connection with transverse tension welds applies generally to butt welds.

Conclusions Concerning Butt Welds.—It is possible that a more intimate study of butt welds would enable a higher strength to be recommended, but meanwhile a value exceeding 16 tons per square inch cannot be assumed for the breaking-strength of butt welds up to $^5/_8$ inch thick made with "mild steel" electrode; and so far as these tests show, that figure can be regarded as reliable both when the welds are chipped off flush and when the "mound" is left on.

For "uranium" electrode, which has a much higher ductility, it appears that a stress of 20 tons per square inch can be relied upon. The tests made were hardly sufficient for deriving suitable data for plates thicker than $^5/_8$ inch, but it is probable that the same values for strength could be assumed for welds up to 1 inch thick, providing the welding is done on both sides when the plate-thickness exceeds $^5/_8$ inch.

It is, no doubt, good practice to put small edge-covers on butt welds to reinforce the ends in some manner. It is also clear that, if a butt weld is used with any suitable welded reinforcement such as the addition of cover-straps with fillets in shear or tension, the full useful strength of the plate can readily be developed.

Compound Welds

In Series 18 (Table IV) tests were made of combined longitudinal and transverse welds, all on plates 9 inches by 1 inch on one side and 12 inches by $^3/_4$ inch on the other side, the lengths of longitudinal welds being 3, 6 and 9 inches, and the tension weld being in all cases 9 inches long. The following table shows that, if a value of 4.8 tons per inch is assumed for longitudinal fillets and 8.0 tons for transverse fillets (reduced by deducting 10 per cent of the length at each end), the values obtained for the reliable strength of the joint are within those observed. Thus the calculated strengths of the welds in Series 18, compared with observed results, would be as follows:—

	Calculated Strength			Average Observed Strength, Tons
	Transverse Fillets	Longitudinal Fillets	Total, Tons	
A	$36 \times 8.0 \times 0.8 = 230$	$12 \times 4.8 = 58$	288	319
B	$36 \times 8.0 \times 0.8 = 230$	$24 \times 4.8 = 115$	345	367
C	$36 \times 8.0 \times 0.8 = 230$	$36 \times 4.8 = 173$	403	406

In Series U 22 (Table VI), the test-pieces which were made with "uranium" electrode, a form of joint was tested in which the weld is at an angle to the line of stress and represents a hybrid between a transverse and a longitudinal weld; it is, therefore, subjected to a stress which is partly shear and partly tension. The breaking-strengths of the three specimens tested were 123, 129 and 142 tons, respectively, or 5.4, 5.7 and 6.3 tons per inch. These values per inch correspond to a reliable strength of $0.8 \times 8.0 = 6.4$ tons per inch for a transverse fillet, and of 4.8 tons per inch for a longitudinal fillet. The mean of the two values, that is, 5.6 tons per inch, agrees closely with the result of the tests. It may therefore be assumed that for inclined fillets the load allowable per inch is a mean between the strength of the transverse and longitudinal fillets, and exceeds the strength of the longitudinal fillet by an amount proportional to the angle of slope of the length of the fillet to the axis of stress. No slope other than 45 degrees was tested, but it would appear to be an unreasonable assumption that values could be obtained similarly for other angles. This type of joint would appear to be very suitable for connections where it is practicable, as the stress tends to be very evenly distributed over the weld and plate with a short length of weld.

Series U 19, 20 and 21 (Table VI) are types of reinforced butt joint, and, as previously stated, the strength of the butt weld is such that, with the reinforcement provided by the three methods dealt with in these three series of tests, the weld has a strength exceeding that of the plate. In tests U 19 C and 20 C the welds on the reinforcing bar were cut off, so that the test in these cases is of the butt weld alone, without reinforcement.

Tests on Wide Plain Plates

These tests were made to ascertain the strength of wide plates such as had been used in the transverse-fillet and butt-weld specimens, as compared with small standard test-pieces. Several pieces of $^3/_8$-inch plate, 8 inches wide and 4 feet 6 inches long, were cut from the batch of plates that had been used for the welding tests. At the same time standard test-pieces were taken from the same plate. The plates were sheared to size, with parallel edges, but not otherwise prepared. The small test-pieces were milled down to $1^1/_2$ inches wide for a length of $8^1/_2$ inches, in accordance with standard practice. The following breaking-strengths were obtained:—

Wide Plates			Standard Test-Pieces		
No.	Yield-Stress,[1] Tons per Square Inch	Breaking-Stress, Tons per Square Inch	No.	Elastic Limit,[2] Tons per Square Inch	Breaking-Stress, Tons per Square Inch
Q1	16.6	27.6	QA	15.8	30.7
Q2	17.0	29.0	QB	15.6	30.2
Q3	17.0	29.0	QC	15.9	31.1

[1] Yield-point indicated by drop of beam.
[2] The elastic limit is the stress at which permanent set occurred, as measured by dividers.

These tests indicate the reduction in strength of plates of the sizes used in practice, as compared with narrow prepared specimens. The average strength for the wide plates is 28.5 tons and for the test-pieces 30.7 tons, per square inch.

Properties of the Weld-Metal

Several tests were made on representative welds to determine the chemical and physical properties of the deposited weld-metal.

Chemical Analysis.—The following is an average percentage analysis of samples of weld-metal taken from the broken specimens:—

	Carbon	Manganese	Sulphur	Phosphorus
"Mild steel"	0.06	0.10	0.03	0.04
"Uranium"	0.06	0.52	0.03	0.04

Tension Tests.—Solid pieces of weld-metal, 1 inch square and 12 inches long, were built up by the deposition of No. 8 electrodes. These were planed to $^{3}/_{4}$ inch square and turned to $^{5}/_{8}$-inch diameter for a length of $4^{1}/_{2}$ inches. The following results were obtained:—

Electrode	Yield-Point, Tons	Breaking-Load Tons	Yield-Stress, Tons per Square Inch	Ultimate Strength, Tons per Square Inch	Elongation on 2 Inches, Per Cent
"Mild Steel"	...	7.1	..	23.2	17
"Uranium"	6.0	9.8	19.6	32.0	25

Izod Impact Tests.—Standard Izod test-bars were built up entirely of weld-metal, of both "mild steel" and "uranium" electrodes. The results obtained were as follows:—

						Foot-Lbs.
"Mild Steel"—(1)	47	47	49	..	Average	48
(2)	44	41	42	..	Average	42
"Uranium" —(1)	49	59	51	44	Average	51
(2)	51	46	41	43	Average	45

These results compare very favorably with those obtainable with ordinary mild steel.

Modulus of Elasticity.—Tests made to determine the elastic properties of the weld-metal gave the following values of Young's modulus:—

"Mild Steel"	11,500 tons per square inch
"Uranium"	12,500 tons per square inch

The value for British Standard structural steel being about 13,000 tons per square inch, it will be seen that the "uranium" weld-metal possesses an advantage in having an elastic modulus more nearly equal to that of the parent metal.

Pressure Welding of Low-Carbon Steels with Theoretical Considerations on the Mechanism of Such Welding

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PART 1

THE paper describes an investigation on the pressure welding of low-carbon steels. The work necessitated a reproducible mechanical means of making the weld and also a test that would indicate the nature and completeness of the union. An apparatus including a high-temperature furnace was devised for making the welds, and the ordinary tensile pulling test in correlation with macroscopic and microscopic observations was used as a means of examining the result.

Initially it was intended to devise some simple test of weldability, but as the experimental work progressed, it soon became clear that with our limited knowledge of the exact nature of the mechanism of pressure welding it was impossible to interpret our results or to devise a simple test of weldability. Hence, it was manifestly necessary first to study the mechanism of such welding and attempt to elucidate the fundamentals underlying the so-called welding of steel by pressing together two metal surfaces.

It also became evident that it was necessary to define the term "welding." In many early experiments when two heated rods were pressed together and then pulled in the cold, very high tensile values were obtained, and yet the fracture took place exactly in the line of junction except for a few small scattered areas. In other words, the rods pulled apart just as they were before being "stuck" together and had certainly not welded completely, despite the high value indicating the strong cohesive force operating. In this paper, welding has been considered as a form of intimate contact between two metal surfaces, so that the units lose their individual identity and there is no change in physical properties in passing through the weld from one unit to the other. This is defined as "true welding." When true welding has taken place completely over the whole section, the probability is that the rupture in tensile test will occur outside the weld.

In the tabulated data given in the paper, most of the information concerns welds which were not "true" and therefore broke in the junction. Naturally, specimens which provided a complete true weld assisted little in the analysis of the nature of the weld, and therefore attention is particularly focused on either partial welding or lack of welding.

The literature is practically devoid of any experimental or theoretical work on the mechanism of pressure welding, but reference must be made to some extremely interesting work by H. Esser,[1] which was published after the completion and filing of the present work. The aim of that author was to find a numerical expression for degree of weldability. The welding experiments were conducted in vacuo under pressure, using pure iron in the earlier tests. The tensile strength was used as a measure of weldability. Pressures of 1, 2 and 3.5 kg. per sq. cm. were used on surfaces prepared to varying degrees of smoothness. It was shown that the finer the grain size and the greater the pressure used, the better the weldability. Surface condition was shown to have considerable influence and it was stated that the coarser the polish,

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[1] H. Esser, "Weldability of Iron," *Archiv. für Eisenhüttenwesen*, 4, 199–206 (1930).

the higher the optimum temperature of welding. A peculiar line of demarcation was illustrated in the microstructure of welds made at 910° C. In carbon steels, there was shown to be a decrease in the temperature range of good weldability as the carbon content was increased.

Apparatus and Materials Used in Present Investigation

The Furnace

On account of the high temperatures which of necessity must be maintained for prolonged periods in experimental work on pressure welding, no small commercial furnace was available. Efforts were directed, therefore, to the development of a small high-temperature furnace which would be robust and afford some control of furnace atmosphere and which would withstand the corrosive action of the oxide slag formed during heating and during the operation of welding. A platinum resistance furnace was considered unsuitable for the work and an electric resistor type appeared to be the only alternative. The final form of the furnace is shown in Figs. 1 and 2. The furnace withstood continued heating and cooling over several weeks without attention. The temperature of operation was 1400° to 1450° C.

In the early experiments an inner tube of alundum was

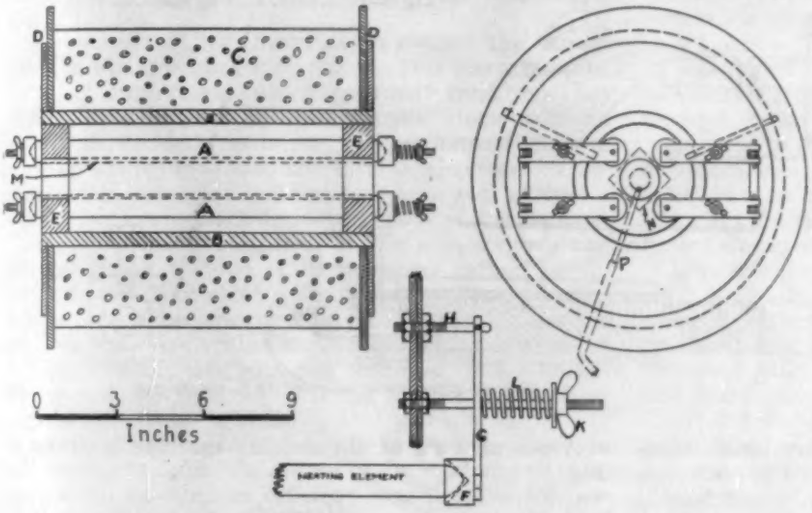

Fig. 1—High-Temperature Welding Furnace

A. "Globar" carborundum heating elements.
B. Alundum tube.
C. Kieselguhr refractory.
D. Asbestos end boards.
E. Alumina-alundum cement refractories.
F. High-chromium alloy.
G. Silvered steel scrap.
I, K, H. Spring contact for Globar.
M. Silica tube.
N. Kieselguhr refractory.
P. Copper tube for hydrogen atmosphere.

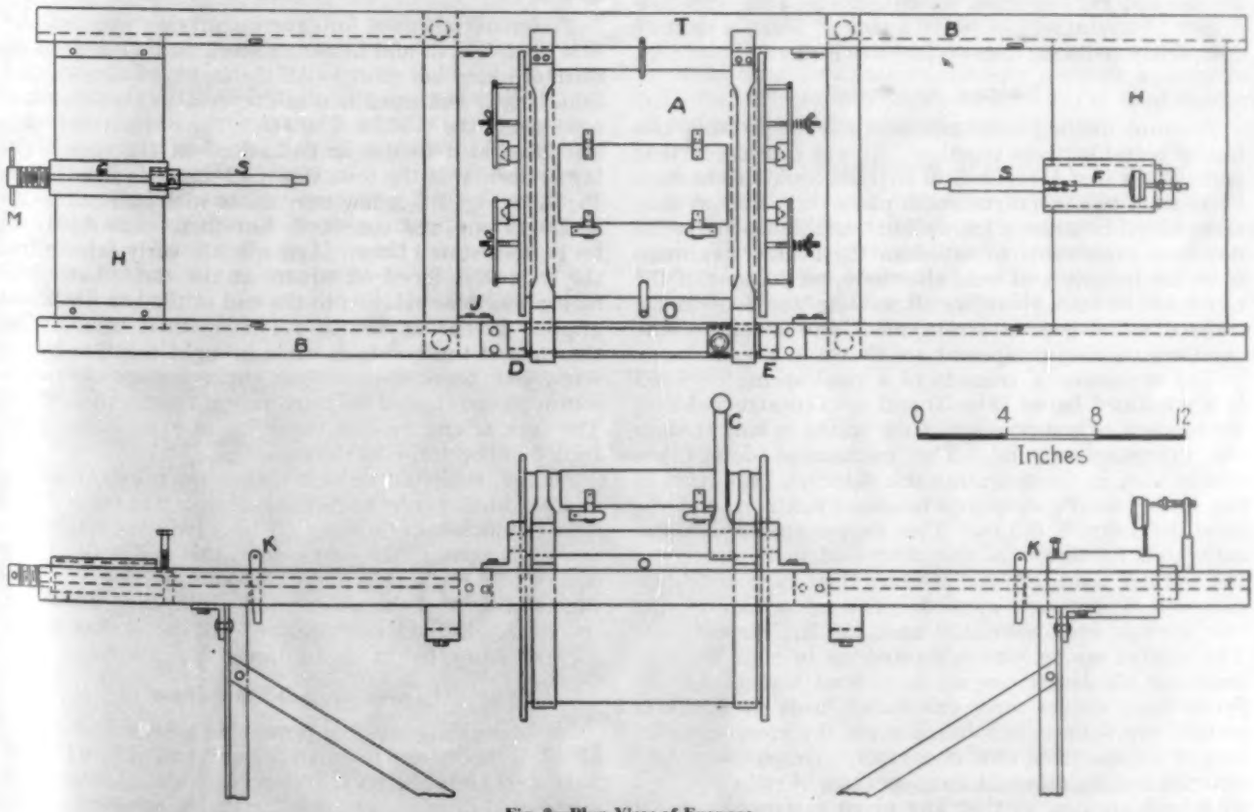

Fig. 2—Plan View of Furnace

A. Furnace detailed in Fig. 1.
B. Rigid main members of welding machine.
C. Arm to rotate furnace from welding position about fulcrum *DE* to test alignment of specimens *S S*.
F, G. Test specimen holders.
H. Slide plates moving in grooves in *B* to stops *J*.
K. Wedges to lock slide plates in constant position.
F. Pressure - indicating specimen holder (Fig. 3).
G. Pressure - applying specimen holder (Fig. 4).
O. Observation tube.
T. Thermocouple tube.

used in the furnace to enclose the test rods, to protect them from the heating units and to equalize the temperature. The amount of oxide dripping from the rods was so great that the tube quickly became useless on account of the slagging action. For such experiments, therefore, the inner tube was discarded. Later, when experiments were conducted in hydrogen, a glazed silica tube (*M*) proved completely satisfactory under these conditions. The hydrogen was introduced at both ends of the furnace, through a copper tube (*P*), and burned at the end remote from its entrance. This was confirmed by operating one jet at a time. Thus, a definite completely reducing atmosphere was insured.

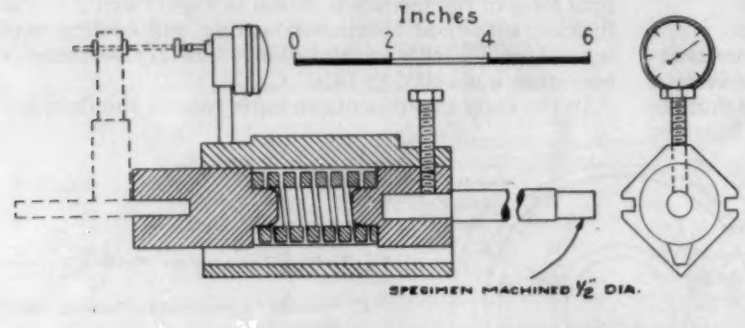

Fig. 3—Pressure-Indicating Specimen Holder

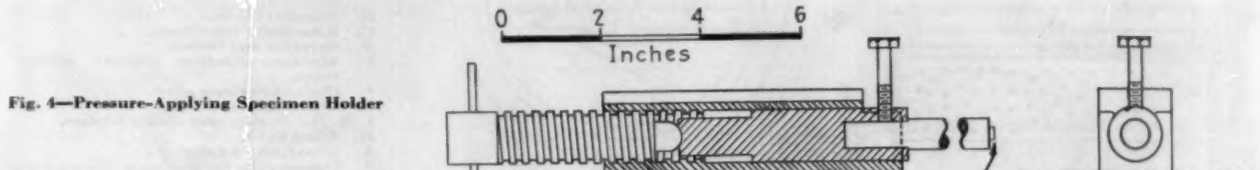

Fig. 4—Pressure-Applying Specimen Holder

Welding Equipment

Pressure welding consists essentially of pressing two heated metal surfaces together. It was considered that perhaps the best experimental analysis could be obtained by heating two metal rods with plane ends and pressing them together under a known but variable load. It did not seem practicable to withdraw the heated specimens from the furnace and weld elsewhere, on account of the rapid loss of heat, therefore all welding was done in the furnace. The general arrangement and details of the complete welding equipment are shown in Fig. 2.

The apparatus *F* consists of a steel spring enclosed in a machined barrel (Fig. 3) and is so constructed that the amount of compression of the spring is indicated on the extensometer dial. The mechanical details are clearly seen in the diagrammatic sketch. Deflection of the spring can be measured to about 0.001 in. and the total deflection is 0.2 in. This simple mechanism was calibrated by means of the dead-load method for the two springs used. A dial reading then gave a definite measure of pressure applied. The capacities of the two springs used were 150 and 350 lb., respectively. The smaller spring was calibrated up to a 62-lb. dead load and the larger one up to a dead load of 140 lb. From these values were calculated loads in terms of pounds per square inch based upon the cross-sectional area of the specimen rods in contact. Graphs were constructed for the different cross-sections of rod-ends used with both springs, so that any given extensometer dial reading could be immediately translated into terms of pounds per square inch pressure.

The specimen holder *G* (Figs. 2 and 4) provides a means of applying the required pressure through a screw-jack arrangement. This pressure applicator and the pressure indicator were lined up in the members *B*, so that on sliding up to their fixed position against the stops *J*, the specimens *S* were properly aligned. Then when the screw handle *M* was turned, the two rods were caused to meet so that the plane machined ends correctly registered.

A general view of the welding machine is shown in Fig. 5.

Materials

The materials used for experimentation were low-carbon open-hearth and bessemer steel, and all were in the form of round bar stock. All the test bars were cut to a 9-in. length and machined at one end, so that they self-centered in the holders *F* and *G*. The contact ends were also machined to size and faced off at the ends. The larger portion of the tests was made on rods shaped as in Fig. 3 or Fig. 4. A few were made with ball and socket and with cup and cone ends but these were ruled out, for reasons stated later. Again, in the early experiments the rods were faced off square at the end. Later, this facing was done relative to the end of the bar which was gripped in the apparatus. This method insured that the ends of the two bars when brought together by the screw-jack touched over their entire surface of possible contact, even though the bars were not perfectly straight. The type of end used in the different experiments is recorded in the various tables.

Finally, it should be stated that when experimenting under oxidizing conditions the mill scale was not removed from the surface of the bars. Under reducing conditions, sudden heating of the bars caused this mill scale to chip off before it could be reduced and this, of course, reacted with and slagged the silica tube. In hydrogen welding, therefore, all bars were cleaned on the surface before they were inserted in the furnace.

Experimental Procedure

In the welding test the furnace was heated about 10° to 15° C. above the required temperature before the test rods were introduced. The cooling effect caused the furnace to drop about 100° C., and some five minutes were required for the furnace to attain again the desired temperature. During this period the rods were kept a little apart. A pressure was then applied to force the two ends into intimate contact, the amount of pressure

being determined by the temperature of the test and the diameter of the ends of the rods at the point of meeting. This pressure usually was maintained with constant temperature for 2 min., after which the pressure was released and the composite bar was immediately removed from the furnace and allowed to cool in still air. As a check on the progress of heating or welding, the rod tips in contact were watched through a blue glass window fitted on the end of the observation tube that passed into the center of the furnace (Fig. 2). This tube was used also from time to time as a means of optically checking the temperature recorded by the thermoelectric couple. The method of observation was especially valuable in examining the formation and action of the liquid oxide during the test.

Occasionally it was desirable to control the atmosphere in which welding took place. This was attempted by using natural gas, which produced conditions but slightly oxidizing, and by hydrogen gas, which produced conditions decidedly reducing. When natural gas was used it was injected into the furnace chamber via the observation tube and sufficient gas was used to give a stream of carbon black from both ends of the furnace. The natural gas decomposed at the temperatures employed, giving a cloud of incandescent carbon within the furnace. When hydrogen gas was used a fused silica tube of 1-in. diam. was inserted into the furnace and the welding was done within this tube. This confined the hydrogen in contact with the test rods, sufficient gas being used to effectively seal the interior of the tube against the admission of air.

Several methods of testing the welds were used in attempting to define the nature of the weld and to compare welds made under different conditions, as follows:

Method 1.—Physical testing by pulling the welded bars in tension and observing the ultimate strength, the elongation and the relative areas of the fracture that welded and that apparently failed to weld. This refers to test bars that broke in the weld, and naturally it was only from such tests that any fundamental information might be gained as to the nature of the weld. The bars were pulled "as welded" or the composite rod was machined to a parallel section over 1 or 2 in. of length, to enable an accurate elongation percentage to be recorded.

Method 2.—Testing the weld under transverse impact blows to determine the toughness or brittleness of the weld and, as before, to note the relative area of surface welded.

Method 3.—Microscopic examination of longitudinal sections of the composite bar cut through the center of the weld. From such an examination it was possible to observe the completeness of welding, the crystal structure of the steel and the presence of burning and oxide inclusions.

Method 4.—Electrical resistivity measurements through the welded section. The bars were machined to 0.315-in. diam. over a length of 2 in. with the weld at the center of the parallel portion. With a steady current flowing, the potential drop along various lengths of the bar down to a 1-mm. length was measured over sections including the weld and compared with similar sections of the same bar not containing the weld. The observations were made by means of the ordinary knife-edge method on a Leeds & Northrup modified type K potentiometer. It was hoped that such measurements might indicate the relative area of true welding over the section without recourse to the fracture or breaking test.

In order to study more accurately the influence of atmosphere, especially a reducing atmosphere, and of very light pressure on weldability, it was decided that the vacuum induction furnace would provide a readily controlled atmosphere. For this purpose two small cylinders of low-carbon open-hearth steel were prepared, measuring 1 by $^1/_2$ in. in diameter, the ends ground flat and polished. The two were stood one upon the other, their polished faces in contact, and placed in the induction furnace. After the furnace chamber had been evacuated and filled with hydrogen, they were heated to about 1200° C. for about 20 min. in a stream of the purified gas and allowed to cool in the furnace. The flow of hydrogen was continued until the specimens were quite cool. This work was repeated using cylinders of 1-in. diam. A similar experiment was made in the induction furnace after producing a film of oxide on the polished surfaces by bluing in air and then heating and cooling in vacuo. In all of these experiments the only pressure tending to push the surfaces into close contact was the dead weight of one piece of metal resting upon the other.

Experimental Results

About 300 welds were made under varying conditions, and approximately one-third of these were tested in tension. The others were examined microscopically or were broken by impact or bending. The results obtained in the early stages of the investigation showed markedly that a correlation of micro-examination and tensile values

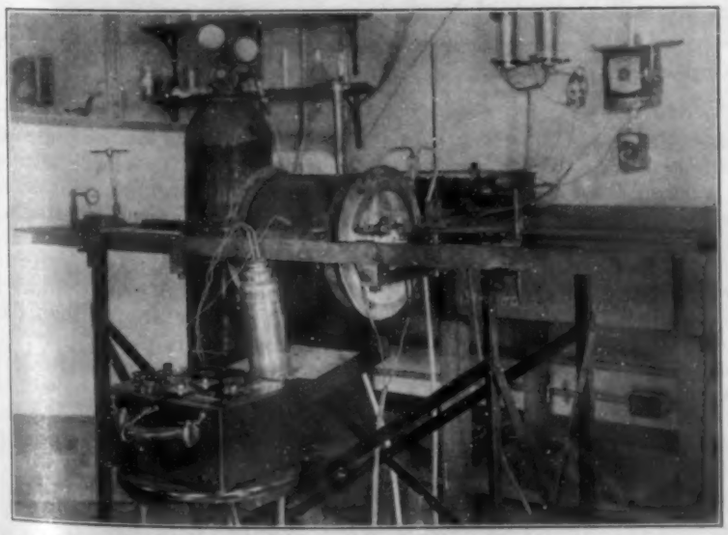

Fig. 5—General View of Welding Furnace

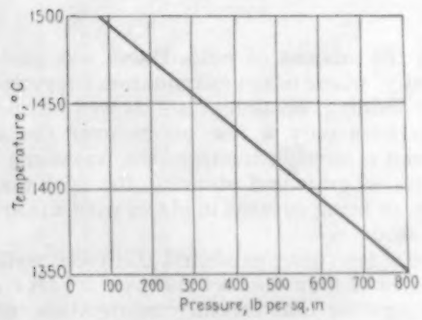

Fig. 6—Relation between Welding Pressure and Temperature

TABLE 1.—*Tests on Bessemer Steel*

Material, ½-in. Diameter Bessemer Rod. Identification Mark, *X*

Test No.	Conditions of Welding				Mechanical Tests				Remarks Re Fracture		
	Atmosphere	Temp., Deg. C.	Pressure, Lb. per Sq. In.	Diameter of Tip, In.	Diameter of Section Tested, In.	Ultimate Strength, Lb. per Sq. In.	Elongation		Fiery, Per Cent	Gray, Per Cent	Treatment
							Per Cent in 1 In.	Per Cent in 2 In.			
	Stock material				0.300	67,300	42.5		As received		
	Stock material				0.300	67,400		37.5	As received		
	Stock material				0.300	66,355	36.0		Heated 1425° C.		Air cooled
	Stock material				0.300	67,200		30.0	Heated 1425° C.		Air cooled
147[a]	Air	1425	550	0.48	As welded	30,000			80	0	Rotated, burned
150[a]	Air	1425	550	0.48	As welded	48,000			75	20	Rotated
152	Air	1425	220	0.48	As welded	41,500			45	30	Rotated
153	Air	1425	220	0.48	As welded	42,500			60	10	Rotated
154	Air	1425	240	0.48	As welded	52,300			75	10	Rotated
155	Air	1425	220	0.48	As welded	32,910			30	60	Rotated, burned
156	Air	1425	240	0.48	As welded	54,500			60	20	Rotated
157	Air	1425	220	0.48	As welded	55,300			70	15	Rotated
158	Air	1425	220	0.48	As welded	46,000			50	30	Rotated, burned
159	Air	1425	220	0.48	As welded	34,600			50	20	Rotated, burned
167	Air	1425	180	0.48	0.315	47,900			40	40	
169	Air	1425	180	0.48	0.315	28,900			5	30	
172	Air	1425	200	0.48	0.315	57,500			55	40	Rotated, burned
176	Air	1425	200	0.48	0.315	59,500			75	20	Rotated
180	Air	1425	200	0.48	0.315	64,300			80	15	Rotated
181	Air	1400	200	0.48	0.315	51,100			40	25	
184	Air	1400	20	0.48	0.315	36,100			5	70	Rotated
202	Hydrogen	1425	280	0.48		66,000		5	80	15	
215	Hydrogen	1425	600	0.48		67,000		10	80	15	
218	Hydrogen	1100	600	0.48		24,000			5	20	
229	Hydrogen	1425	680	0.25	As welded	68,000			60	20	
230	Hydrogen	1425	470	0.25	As welded	46,000			50	5	
231	Hydrogen	1425	370	0.25	As welded	82,000[b]			85	10	
232	Air	1425	680	0.25	As welded	37,000			25	40	
233	Air	1425	470	0.25	As welded	53,000			25	55	
236	Hydrogen	1425	350	0.25	As welded	80,000[b]			95	0	
237	Hydrogen	1425	450	0.25	As welded	79,000[b]			Broke outside weld		
238	Hydrogen	1425	600	0.25	As welded	78,000[b]			75	15	
239	Air	1425	600	0.25	As welded	11,000					Burned
240	Air	1425	600	0.25	As welded	12,000					Burned
241[c]	Hydrogen	1425	330	0.375	0.320	65,200			95	5	
242[b]	Hydrogen	1425	200	0.375	0.320	44,300			70	0	
243[c]	Hydrogen	1425	450	0.375	0.320	63,700			80	10	
244[c]	Hydrogen	1425	330	0.375	0.320	12,500			25	5	
245[c]	Hydrogen	1425	450	0.375	0.345	59,000			75	10	
249[c]	Hydrogen	1400	550	0.375	0.289	64,200	13		80	10	Annealed
250[c]	Hydrogen	1400	550	0.375	0.289	62,600	14		50	45	Annealed
251[c]	Hydrogen	1400	550	0.375	0.289	52,400	4		50	30	
252[c]	Air	1400	550	0.375	0.289	63,900	16		20	75	Annealed
253[c]	Air	1400	550	0.375	0.289	64,900	19		25	65	Annealed
254[c]	Air	1400	550	0.375	0.289	65,900	16		80	15	
255	Hydrogen	1425			0.289	62,600	30				Annealed stock
256	Hydrogen	1425			0.289	65,100	32				Stock test

[a] Cup and cone shaped ends. [b] High values due to upsetting. [c] Ends trued.

with the amount of welded area was misleading. Frequently, where micro-examination suggested nearly complete welding, breaking tests showed but partial welding. Sometimes only a few points over the whole surface showed a metallic fracture, the remaining surface being bright or gray and showing the tool marks from the lathe, or being covered in places with a thin layer of black iron oxide.

Very few tests exhibited complete welding over the full area of their contact surfaces. This condition made it imperative that careful consideration be given to the area welded in order to study the progress of welding, rather than placing too much credence on tensile and microscopic observations. These relatively small welded areas often gave exceptionally high tensile values.

Many welds, apparently perfect as viewed under the microscope and having as much as 80 per cent of the full tensile strength of the steel, showed as low as some 30 to 40 per cent crystalline fracture. The welds showing high strengths as compared to their welded areas were identical with those which had low impact resistance.

In the tables, under the heading Remarks Re Fracture, a figure is given for the area welded, which is an estimation of the percentage of sectional area of true weld and can be only approximate. It will be shown that the total weld consists of two component parts, giving a crystalline and a gray fracture in tensile rupture. Minute unwelded areas frequently occur intimately dispersed throughout the gray fracture, hence the accurate estimation of area of gray fracture is extremely difficult and uncertain.

With reference to the high tensile values obtained with insufficient welded area to explain such values, some discussion is opportune. In many cases in the tabulated

TABLE 2.—*Tests on Bessemer Steel*

Material, ½-in. Diameter Bessemer Rod. Identification Mark, *Z*

Test No.[a]	Conditions of Welding				Mechanical Tests				Remarks Re Fracture		
	Atmosphere	Temp., Deg. C.	Pressure, Lb. per Sq. In.	Diameter of Tip, In.	Diameter of Section Tested, In.	Ultimate Strength, Lb. per Sq. In.	Elongation		Fiery, Per Cent	Gray, Per Cent	Treatment
							Per Cent in 1 In.	Per Cent in 2 In.			
	Stock material				0.300	68,750	40.0		As received		
	Stock material				0.300	68,670		33.5	As received		
	Stock material				0.300	67,060	39.0		Heated 1425° C.		Air cooled
	Stock material				0.300	66,770		30.5	Heated 1425° C.		Air cooled
278	Air	1425	420	0.375	0.300	25,320	0				Rotated, burned
279	Air	1425	380	0.375	0.300	38,060	0				Rotated, burned
280	Air	1400	420	0.375	0.300	68,900	30.0		Broke outside weld		Rotated
281	Air	1400	400	0.375	0.300	64,650	12.0		20	75	Rotated
282	Air	1400	100	0.375	0.294	38,340	0		20	60	Rotated
283	Air	1400	100	0.375	0.300	57,150	8.0		35	60	Rotated
284	Air	1375	420	0.375	0.300	67,770	18.0		0	100	Rotated
285	Air	1375	420	0.375	0.300	66,490	17.0		60	40	Rotated
286	Air	1375	240	0.375	0.300	65,220	14.0		70	30	Rotated
287	Air	1375	160	0.375	0.300	44,560	0		5	75	Rotated
288	Air	1375	630	0.375	0.300	60,130	0		10	60	
289	Air	1375	200	0.375	0.300	37,350	0		10	40	
290	Air	1350	400	0.375	0.300	64,650	12.0		70	30	Rotated
291	Air	1350	500	0.375	0.300	63,380	8.0		50	35	Rotated
292	Air	1350	700	0.375	0.300	67,620	22.0		60	40	Rotated
293	Air	1350	900	0.375	0.300	68,050	18.0		50	50	Rotated
294	Air	1350	900	0.375	0.300	54,470	0.0		40	20	Rotated
295	Air	1350	700	0.375	0.300	52,490	0.0		10	40	
296	Air	1350	500	0.375	0.300	45,550	0.0		20	20	
297	Air	1350	1100	0.375	0.300	59,280	0.0		25	35	
303	Hydrogen	1425				67,000	35.0				Stock test
304	Hydrogen	1425				66,350		31.0			Stock test

[a] Ends trued in all tests.

TABLE 3.—*Tests on Open-hearth Steel*

Material, ½-in. Diameter Open-hearth Rod. Identification Mark, *Y*

Test No.	Conditions of Welding				Mechanical Tests				Remarks Re Fracture		
	Atmosphere	Temp., Deg. C.	Pressure, Lb. per Sq. In.	Diameter of Tip, In.	Diameter of Section Tested, In.	Ultimate Strength, Lb. per Sq. In.	Elongation		Fiery, Per Cent	Gray, Per Cent	Treatment
							Per Cent in 1 In.	Per Cent in 2 In.			
	Stock material				0.300	48,520	53.0		As received		
	Stock material				0.300	48,100		41.0	As received		
	Stock material				0.300	51,640	43.0		Heated 1425° C.		Air cooled
	Stock material				0.300	49,940		35.5	Heated 1425° C.		Air cooled
143	Air	1425	550	0.48	As welded	46,000			90	0	Rotated
144	Air	1425	550	0.48	As welded	41,000			55	25	Rotated
145	Air	1425	550	0.48	As welded	45,000			60	25	Rotated
160	Air	1425	240	0.48	As welded	40,900			70	15	Rotated
161	Air	1425	220	0.48	As welded	40,500			50	35	
162	Air	1425	220	0.48	As welded	41,100			60	30	
164	Air	1425	220	0.48	As welded	39,800			60	20	
165	Air	1425	220	0.48	As welded	42,700			70	15	
166	Air	1425	220	0.48	As welded	32,800			15	35	Oxide rings
174	Air	1425	200	0.48	0.315	42,700			50	25	
175	Air	1425	180	0.48	0.315	46,400			55	40	Rotated
178	Air	1425	200	0.48	0.315	40,700			45	25	
179	Air	1425	200	0.48	0.315	44,300			45	45	Rotated
185	Air	1400	200	0.48	0.315	42,000			25	50	
188	Air	1400	20	0.48	0.315	30,900			40	25	Rotated
190	Air	1325	400	0.48	0.315	34,800			20	55	Rotated
200	Hydrogen	1425	280	0.48	0.315	54,470		7.5	40	45	
212	Hydrogen	1425	280	0.48		60,000		17.0	0	85	
214	Hydrogen	1425	600	0.48		46,000			10	20	
225	Hydrogen	1425	1090	0.25	As welded	79,000[b]			100	0	
226	Hydrogen	1425	680	0.25	As welded	77,000[b]			20	70	
227	Hydrogen	1425	470	0.25	As welded	58,000[b]			50	20	
228	Hydrogen	1425	370	0.25	As welded	55,000[b]			50	25	
234	Air	1425	680	0.25	As welded	58,000[b]			20	60	
235[a]	Air	1425	470	0.25	As welded	57,000[b]			60	30	
270[a]	Air	1400	480	0.375	As welded	27,000			0	40	
271[a]	Air	1400	420	0.375	As welded	36,600			0	70	
272[a]	Hydrogen	1425	420	0.375	0.30	51,000	15.0		90	5	
273[a]	Hydrogen	1425	420	0.375	0.30	48,800	16.0		30	60	
274[a]	Hydrogen	1425	550	0.375	0.30	50,000	28.0		5	90	
275[a]	Hydrogen	1425	550	0.375	0.30	50,400	24.0		0	95	
276[a]	Hydrogen	1425	700	0.375	0.30	52,600	36.0		Broke outside weld		
260	Hydrogen	1400	330	0.375	0.30	34,000			0	25	
263[a]	Hydrogen	1400	550	0.375	0.30	31,600			0	40	

[a] Ends trued. [b] High values due to upsetting.

data efforts have been made to present an estimation of the amount of gray structure along with the amount of fiery or crystalline structure. Total or true weld refers to the summation of the fiery and gray structures.

A few instances will be cited to indicate how the total true fracture cannot account for the whole of the tensile value given by the welded section. Tests 111, 115, 125 (Table 4) and 171 (Table 5) on open-hearth steels show

TABLE 4.—*Tests on Open-hearth Steel*

Material, 7/16-in. Diameter Open-hearth Rod. Identification Mark, *B*

Test No.	Conditions of Welding				Mechanical Tests				Remarks Re Fracture		
	Atmosphere	Temp., Deg. C.	Pressure, Lb. per Sq. In.	Diameter of Tip, In.	Diameter of Section Tested, In.	Ultimate Strength, Lb. per Sq. In.	Elongation		Fiery, Per Cent	Gray, Per Cent	Treatment
							Per Cent in 1 In.	Per Cent in 2 In.			
	Stock material				0.4375	51,630		52.0	As received		
6	Natural gas	1500	200	0.3	As welded	28,000					
86	Air	1450	600	0.375	As welded	44,420		5.0	10	60	
87	Air	1450	600	0.375	As welded	48,450		14.0	10	70	Burned
108	Air	1450	315	0.375	As welded	42,000		8.0	95	0	Burned
109	Air	1450	315	0.375	As welded	38,760		10.0			
110	Air	1450	315	0.375	As welded	27,940		8.0	5	60	
111	Air	1450	295	0.375	As welded	39,040		2.0	5	50	Burned, oxide rings
115	Air	1450	280	0.375	0.315	37,700			10	60	Burned
120	Air	1425	450	0.375	0.315	41,650			35	40	
122	Air	1425	450	0.375	0.315	44,580			50	30	
123	Air	1400	500	0.375	0.315	48,020			15	80	
124	Air	1400	500	0.375	0.315	48,660			45	40	
125	Air	1400	575	0.375	0.315	52,860			55	25	
131	Air	1375	500	0.375	0.315	49,900			30	50	
137	Air	1425	500	0.375	0.315	50,950			30	60	
140[a]	Air	1425	420	0.375	As welded	32,000			60	20	Rotated
141[a]	Air	1425	450	0.375	As welded	22,500			40	30	

[a] Cup and cone shaped ends.

TABLE 5.—*Tests on Various Steels*

Material, Miscellaneous and Noted in Last Column. The First Five Items Refer to the Experimental Results on Impact Welding

Test No.	Conditions of Welding				Mechanical Tests				Remarks Re Fracture		
	Atmosphere	Temp., Deg. C.	Pressure, Lb. per Sq. In.	Diameter of Tip, In.	Diameter of Section Tested, In.	Ultimate Strength, Lb. per Sq. In.	Elongation		Fiery, Per Cent	Gray, Per Cent	Treatment and Steel[a]
							Per Cent in 1 In.	Per Cent in 2 In.			
126	Air	1400		0.375	0.315	37,200			35	50	Impact welded, *B*
127	Air	1400		0.375	0.315	42,800			20	65	Impact welded, *B*
138	Air	1425		0.375	0.315	30,570			10	65	Impact welded, *B*
170	Air	1425		0.48	0.315	41,300			35	40	Impact welded, *Y*
171	Air	1425		0.48	0.315	43,100			30	30	Impact welded, *Y*
31	Natural gas	1450	200	0.3	As welded	22,400					*D*
50	Air	1450	900	0.625	As welded	11,400					*A* burned
51	Air	1450	850	0.5	As welded	17,200					*A* burned
52	Natural gas	1450	875	0.575	As welded	48,000					*A*
193	Air	1425	280	0.48		44,850			5	50	*X* and *M*
197	Air	1425	280	0.48		67,760		10.0			Rotated *X* and *M*

[a] *M* = medium carbon steel.

TABLE 6.—*Details of Welds Illustrated in Figs. 7 to 30 Inclusive*

Figure No.	Test No.	Conditions of Welding			Mechanical Tests	Remarks Re Fracture	Material
		Atmosphere	Temp., Deg. C.	Pressure, Lb. per Sq. In.			
6	135	Air	1425	375	Fractured by bending		Open hearth
7	132	Air	1375	500	Fractured by bending	50 per cent fiery	Open hearth
8, 16	291	Air	1350	500	Ult. 63,380; elong. 8 per cent on 1 in.	60 per cent fiery. Rotated	Bessemer
9	294	Air	1350	900	Ult. 54,470; elong. 0 per cent	25 per cent fiery. Not rotated	Bessemer
10	275	Hydrogen	1425	550	Ult. 50,000; elong. 24 per cent on 1 in.	100 per cent gray	Open hearth
11, 12, 13, 14		Hydrogen	1400	0	Ultimate above 40,000	Fiery	Bessemer
15		Air	1425				Open hearth
17	290	Air	1350	400	Ult. 64,650; elong. 12 per cent on 1 in.	70 per cent fiery. Rotated	Bessemer
18, 19	134	Air	1425	500	Fractured after microexamination	A poor weld	Open hearth
20, 21	98	Air	1426	500			Open hearth
22, 23	77	Air	1425	500	Fractured after microexamination	See text	Open hearth
24, 25	280	Air	1400	420	Ult. 68,900; elong. 30 per cent on 1 in.	Broke outside weld. Rotated	Bessemer
26, 27	213	Hydrogen	1425	600		80 per cent fiery	Bessemer
28, 29	83	Natural gas	1400	200–300			Open hearth

TABLE 7.—*Details of Welds Illustrating Difference in Intrinsic Strength of Welds Made in Air and in Hydrogen*

Test No.	Atmosphere	Temp., Deg. C.	Estimated Fiery Weld, Per Cent	Estimated Gray Weld, Per Cent	Total Weld, Per Cent	Strength of Weld × 100 / Strength of Material, Per Cent	Character of Weld[a]	Material
202	Hydrogen	1425	80	15	95	98	S	Bessemer
215	Hydrogen	1425	80	15	95	100	S	Bessemer
225	Hydrogen	1425	100		100	160	S	Open-hearth
231	Hydrogen	1425	85	10	95	125	S	Bessemer
236	Hydrogen	1425	95	0	95	120	S	Bessemer
237	Hydrogen	1425	100	0	100	120	S	Bessemer broke outside weld
238	Hydrogen	1425	75	15	90	120	S	Bessemer
241	Hydrogen	1425	95	5	100	97	W	Bessemer
249	Hydrogen	1425	80	10	90	96	S	Bessemer
272	Hydrogen	1425	90	5	95	100	S	Open-hearth
273	Hydrogen	1425	30	60	90	96	S	Open-hearth
274	Hydrogen	1425	5	90	95	100	S	Open-hearth
275	Hydrogen	1425	0	95	95	100	S	Open-hearth
123	Air	1400	15	80	95	94		Open-hearth
137	Air	1425	30	60	90	100	S	Open-hearth
160	Air	1425	70	15	85	85		Open-hearth
176	Air	1425	75	20	95	90	W	Bessemer. Rotated
180	Air	1425	80	15	95	95		Bessemer. Rotated
252	Air	1400	20	75	95	95		Bessemer. Rotated
254	Air	1400	80	15	95	98		Bessemer.
281	Air	1400	20	75	95	96		Bessemer. Rotated
283	Air	1400	35	60	95	85	W	Bessemer
284	Air	1375	0	100	100	100		Bessemer
285	Air	1375	60	40	100	100		Bessemer
286	Air	1375	70	30	100	97	W	Bessemer
290	Air	1350	70	30	100	95	W	Bessemer
292	Air	1350	60	40	100	100		Bessemer
293	Air	1350	50	50	100	100		Bessemer

[a] S = strong; W = weak.

a total weld of 55, 50, 80 and 60 per cent of the full section with tensile values corresponding to 80, 75, 105 and 85 per cent of the strength of the parent steel. Likewise, with bessemer steel, tests numbered 253 (Table 1), 294 and 197 (Table 2) show total welds of 70, 50 and 60 per cent of section ruptured, with 97, 80 and 85 per cent tensile strength.

In both instances, therefore, where reference is given to tests which provided only partial welding over the area tested, the ultimate strength of the weld gives a value some 25 to 30 per cent greater than would be expected from the area welded. These anomalous results, coupling high tensile strength with small area of weld and low impact resistance, may be difficult to understand, but a complete explanation of these observations will be attempted later.

A study of the experimental work given in the tables will reveal many of these apparent anomalies and certain inconsistencies. The data have been collected and tabulated for convenience and ready reference and with an effort to show in some quantitative sense the manner of carrying out the experiments and also the results obtained. It must be remembered, however, that the data are *not* quantitatively comparable, because the experimental work is not quantitatively reproducible. Thus, it may be pointed out that one of the most important factors of all is the least reproducible—that is, the contact between the two ends of the rods and the pressure applied to these. Assuming that the ends provide plane surfaces, with the application of small pressure, one part of such surface will touch first, on account of improper alignment. Complete contact and aligning and prevention of bending of the rods are extremely difficult at temperatures of the order of 1400° to 1450° C., more particularly as the welding has to be accomplished inside a small experimental furnace.

On the other hand, the series of tests was somewhat successful in producing good welds. Two of the best, 237 (Table 1) and 276 (Table 3), showed tensile strengths of 79,000 and 52,600 lb. per sq. in., respectively. Both of these broke outside of the weld.

It is also to be noted that many tests were of an exploratory nature, to examine the relative value and effect of the different variables, and in no way an attempt to produce a "good weld" or to provide a test of weldability. This is to be borne in mind emphatically or the results tabulated tend to become very misleading. All data then can be regarded only as qualitative in a relative sense, although individually expressed quantitatively.

Almost all of the welds were made by the static pressure method; i.e., slowly loading the test rods by turning up the screw-jack to the desired pressure and holding the temperature constant for 2 min. Figure 6 is a curve that indicates approximately the relation between the temperature and the pressure which was found to produce welding in an oxidizing atmosphere, other factors being favorable.

This is derived from experience alone and is dependent upon the nature of the experimental conditions, since greater pressures usually cause trouble due to bending of the rods. Of necessity, other pressures than those shown on the curve were used to investigate fully such problems as the effect of pressure on the quantitative removal of the liquid oxide from between the two ends of the test rods. In this connection too much reliance must not be placed upon the pressure as a mathematical measure of the degree of welding to be expected. Similar pressures often produce widely varying amounts of welding, since welding is controlled by the amount of intimate contact obtaining between the two ends of the rod. This contact is largely dependent upon alignment of the two surfaces one with the other, the smoothness or roughness of the surfaces, the resistance of the metal to deformation, and the viscosity of the liquid oxide at the given temperature.

When two tests at different pressures show the same

properties, it is to be inferred that the experimental conditions of the rod-ends were different in one case from the other, and pressures of different magnitudes were required to bring the tips of the rods wholly into contact. Due to the conditions of experimentation, the high pressures noted in the above figure were necessary to produce welds over any appreciable area, although, as will be demonstrated, very little pressure is required, provided intimate contact can be made without its application.

In an attempt to investigate the influence of sudden strain upon the tendency for crystals to grow or absorb one another at elevated temperatures, it was thought that welding or crystalline adhesion might be brought about by the sudden stressing of adjacent crystals while in contact. Accordingly, one rod was fastened rigidly, the other placed against it, and at the proper temperature the two were driven together by sharp blows with a hammer. Although some welding resulted from this treatment, no marked difference from pressure welding was observed. Again the results depended upon the amount of intimate surface contact obtained, and this was a function of the experimental variables stated previously. Some impact data are entered in Table 5 as tests 138, 170 and 171. Finally, it can be said that welding by impact gives much the same results as by the static pressure method, having the experimental disadvantage in the difficulty of reproducing conditions with fair accuracy. Here it should be emphasized that only such impact values were used as to avoid much deformation in the body of metal constituting the tip, and yet sufficient to bring the surfaces into intimate contact. Severe hot working, as in the case of blacksmith welding, is a totally different problem from that under consideration in this paper.

In the earlier stages of experimentation, attention was given only to the amount of oxidation occurring at the various temperatures of welding. With an open furnace such as was necessarily used in this case, a fairly rapid change of atmosphere was obtained by natural draft through the furnace, hence, there was a tendency toward excessive oxidation at any given temperature, compared to that found in a closed heating furnace. It has been demonstrated that the presence of a large amount of available oxygen results in a rapid rise in temperature of the oxidized steel above that of the furnace. This is due to the high rate of chemical combination at 1400° to 1500° C. and to the exothermic character of the reaction, according to the equation: $2Fe + O_2 = 2FeO + 131{,}400$ calories.

From this condition, together with the fact that furnace temperature alone was measured, one can readily understand how burning may occur at temperatures that apparently are safe.

Natural gas was introduced into the furnace in an attempt to decrease the rate of oxidation, rather than to produce a reducing atmosphere. The formation of a smoky flame due to decomposition and incomplete combustion was objectionable and was therefore discontinued. The closing of the ends of the furnace with Kieselguhr blocks carrying a small hole to accommodate test bars appreciably reduced the oxidation. The furnace was shielded from draft as far as possible. Many experiments were also conducted in a hydrogen atmosphere.

It is probable that most interest centers on the mechanism concerned with pressure welding when no protection from the atmosphere is attempted. Nevertheless, it seems important from the theoretical aspect to consider the phenomenon when completely clean oxide-free metallic surfaces are in contact under varying pressures. It was to examine the limiting conditions of welding with such metallic surfaces that the experiments in a hydrogen atmosphere were carried out. This also eliminated one variable and hence gave some assistance in a consideration of the fundamentals of this method of welding. In other words, it permitted an analysis of the effect of the absence of liquid oxide, and allowed observations under conditions otherwise difficult to obtain.

Thus, in conjunction with the regular work done in the welding furnace, some attempts were made to weld pieces of metal in the vacuum induction furnace. This digression was considered of value in as much as very closely controlled conditions of atmosphere could be obtained. Evacuation of the furnace chamber to a high degree resulted in a very small amount of residual gas, which, if having any effect at all, would be but slightly oxidizing. Also, the method presented a ready means of heating in a pure dry hydrogen atmosphere whereby material absolutely free from any oxide film could be prepared.

Accordingly, two cylinders 1 in. long, of low-carbon open-hearth steel, were cut from a $^1/_2$-in. round; one end of each was ground flat in a precision grinder and then polished to a mirror-like surface by hand. These cylinders were placed one on top of the other, their polished faces in contact, and introduced into the induction furnace chamber. The chamber was alternately evacuated and flushed with hydrogen to remove the last traces of air. These specimens were heated to about 1200° C. in a steady stream of hydrogen, and then allowed to cool in the gas-filled chamber. The composite welded cylinder was then machined to a 1-in. parallel section of 0.275-in. diam. and pulled in tension. The tensile value obtained was 24,050 lb. per sq. in. and the fracture showed that about 50 per cent of the machined area had been welded, the fracture having a fiery crystalline appearance. The relatively small welded area in this case can be explained by the difficulty of approximating true plane surfaces with this method of preparation and by the fact that no pressure was used to deform the surfaces into intimate contact.

This experiment was repeated, duplicating all conditions except that the polished surfaces were blued by preheating in air and by conducting the welding test in vacuo instead of in hydrogen. It was believed that a thin film of iron oxide on the surfaces would effectively prevent welding. This was substantiated, since heating to 1200° C. and cooling in vacuo produced no visible indication of a tendency to unite.

A third test was conducted using a low-carbon bessemer steel. The final surface on the ends of the $^3/_4$ by $^1/_2$-in. diam. cylinders was obtained by grinding flat on a 46-grain alundum wheel after drilling a $^3/_{16}$-in. hole down the centers of the cylinders. The holes were drilled to facilitate the preparation of a plane surface. Heating was conducted in a stream of hydrogen at 1400° C. and the steel cooled in the hydrogen-filled chamber. The composite cylinder was then pulled in a tensile machine. Because of the shortness of the specimen, it pulled out of the grips when a load of about 37,000 lb. per sq. in. had been applied without causing failure. A fracture was obtained by vigorously hammering the cylinder while it was held in a vise. True welding extended over the entire surface in contact. One piece had slipped laterally over the other when being placed in the furnace so that each did not present a full circular area to be welded; the fracture had a coarse crystalline appearance. This experiment resulted in perfect welding, and, as in former tests, no pressure was used other than that due to the weight of the upper cylinder.

Two similar cylinders of the same material were prepared as before and heated in the vacuum furnace with a pressure of about 1 mm. of air. This permitted a thin film of oxide to form on the surface of the steel. Heating to about 1400° C. did not result in any welding. The pieces were merely stuck together and readily broke apart under a light transverse shock.

The influence of hydrogen on the properties of the metal was investigated by heating a rod in air to 1425° C. and air cooling, and also heating a similar rod in hydrogen to 1425° C. and air cooling. When tested in tension, the former showed some 1000 lb. per sq. in. more strength than the latter, which indicates that a direct comparison of tensile values is possible so far as the effect of these two atmospheres is concerned. Annealing a hydrogen-treated rod at 650° C. in vacuo reduced the tensile strength somewhat without improving the elongation. In a number of tests the pressure used caused the ends of the rods to upset and a few of these were not machined for tensile test but were pulled "as welded." The resulting high strength was calculated from the initial size, which explains why some tests gave values much higher than the strength of the stock, although breaking in the weld.

In the section devoted to the theoretical considerations of a pressure weld, reasons are put forward to indicate that such welds are frequently imperfect owing to the presence of an oxide layer covering part of the cross-section of the weld. For this reason efforts were made to attempt to measure experimentally the sectional area of such films by means of electrical resistivity measurements. These did not provide very satisfactory results. The electrical resistance is a function of the area of cross-section and the length of the conductor. The length of weld is so minute as to render alterations in the second variable very difficult to analyze. In a few cases, however, a definite difference was noted using the 1-mm. distanced knife-edge contact.

The second half of this article dealing with Microscopic and Macroscopic examinations will be published in the July issue of the Journal.

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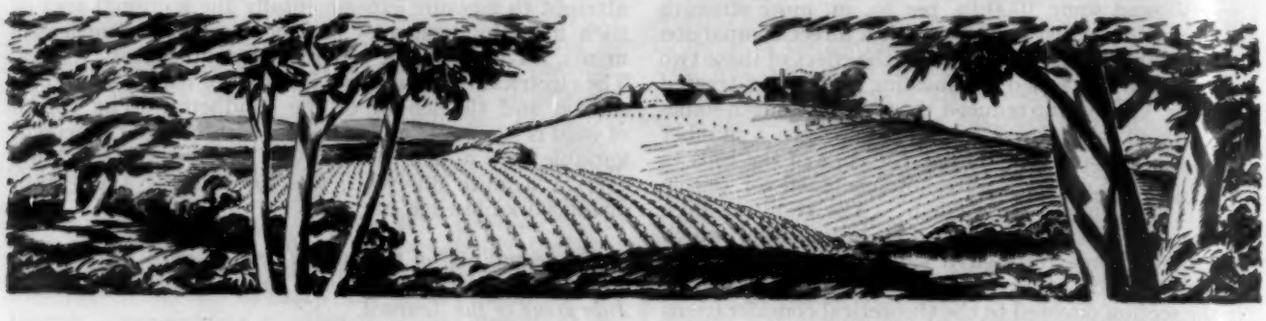

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